BODY SWAY IN RESPONSE TO RETINAL DISPARITIES SIMULATING OCULAR TORSION

By

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This dissertation is dedicated in memory to my maternal grandmother, Elsbeth Antoinette Hosser Dieterle, who adored me and saw scholastic achievement in my future.

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Abstract of Dissertation Presented to the Graduate School
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BODY SWAY IN RESPONSE TO RETINAL DISPARITIES SIMULATING OCULAR TORSION

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The purpose of this investigation was to explore a possible relationship between body sway and motion sickness symptoms evoked by the viewing of selected stimuli. Body sway was measured by an acoustic head tracking device. Motion sickness history and symptoms were measured by a questionnaire used in other laboratories. Seventeen male and 16 female healthy undergraduates participated for course credit. Fifteen males and 13 females completed all trials.

The anaglyph method was used to separate stimuli to the two eyes to control retinal disparity. Static stimulus conditions were (a) binocularly aligned vertical (or horizontal) gratings (no retinal disparity), and (b) gratings rotated (torted) dichoptically +/- 2° from vertical (or from horizontal) to provide a disparity gradient. Vertical dichoptic gratings provided horizontal retinal disparities (stereoscopic depth) consistent with the torted retinal images of a pitched frontal plane. Horizontal dichoptic gratings provided vertical retinal disparities consistent with torted retinal images, and simulated the disparities in cyclophoria (static ocular torsion). Dynamic conditions, half using vertical and half using horizontal orientations moved as roll, pitch, or both. Roll is the kind of retinal image change that simulates cycloversion, and pitch simulates cyclovergence torsional eye movements.

Body sways were compared to a motion sickness score assigned to each subject based on number and severity of symptoms (13 subjects reported nausea or dizziness). Neither RMS position error nor higher moments of the sway distributions (skew, kurtosis) predicted the motion sickness scores. Fourier analysis of the sway waveforms revealed a component locked in frequency to the dynamic stimuli, whose magnitudes did predict the sickness scores.

Stimuli with vertical retinal disparities, typically associated with torsional eye movements, surprisingly were more effective for evoking body sways than were stimuli with horizontal disparities. The present visual stimuli were also unusually potent at inducing motion sickness symptoms.

CHAPTER 1
INTRODUCTION

Body Sway and Vision

Our ability to stand upright and locomote on two legs is rather amazing considering the complexity of the system that maintains our postural stability. Many control mechanisms are involved: sensory and motor systems, musculoskeletal systems, psychological, and reflex systems. From the top down, the vestibulo-ocular reflex maintains our eyes in position as the head moves; cervical reflexes of the neck keep the head in position as the body moves. Spinal reflexes, hip flexor reflexes, tendon reflexes, ankle reflexes, and plantar reflexes of the foot are all components in this postural stability system. The vestibular system also informs us of direction of gravity and linear acceleration. The somatosensory system processes information from the pressure and joint receptors that are incorporated in the above reflexes.

The visual system also plays a very important role in postural stability and body sway. The present investigation is concerned primarily with the contribution of vision, the binocular visual system in particular, to body sway.

Body Sway Measurement

Traditionally, the measurement of static postural stability is known as posturography. Many methods of measuring body sway have been used in the past. Head movements have been measured by visual comparison against a horizontal ruler, traces etched onto smoked glass above a subject wearing a helmet with a spike, and photographing a light strapped to the head of the subject. Displacement of the center of gravity has been measured using spring-loaded platforms, oscillating platforms, and force platforms. Also, electromyography of various postural muscles has been studied (Begbie, 1967).

It is not surprising therefore, that the literature relevant to the topic of body sway suffers from a lack of standardization of measurement. It is difficult to compare observations that "sway increased" or "stability was reduced" across different laboratories. Because body sway is complicated, there are a number of different possible sway measures. These measures may be global, requiring clinical judgement, or specific to a particular joint angle or a specific muscle's EMG. Currently, the most popular method uses a platform that allows the mechanical centers of force to be estimated.

It is not presently possible to precisely correlate the various measures of body sway. There is no apparent solution to this problem, nor is one offered here. This is merely a forewarning that some of the complexity of the literature may be a reflection of the use of measurement techniques that may not be directly comparable (Woods, 1986).

The popular measurement technique referred to previously is known as a stabilometer. A stabilometer consists of a platform mounted either on a spring at each corner or on a central square steel shaft. Strain gauges mounted at the corners, or on each side of the steel shaft, record the pressure changes caused by the swaying of a subject standing in the center of the platform. The platform support is stiff so that its motion is not apparent to the subject. The signals from the strain gauges are usually displayed as two traces on an oscilloscope or pen recorder, one indicating sway in the fore-aft direction and the other in the lateral direction. Assuming that the standing human body behaves as a simple inverted pendulum, with all its motion occurring about the ankle joint, stabilometer measurements permit estimation of movement of the body's center of gravity. Often postural stability is calculated as power spectral density which may then be plotted as a function of frequency (Howard, 1986).

In the present research investigation, the effects of particular visual stimuli on body sway are to be examined. The body sway measure is taken from the head rather than from the feet. There is a significant contribution of head-down processing for postural stability and it is believed that head movement is a valid measure of postural equilibrium because of its contributions to the maintenance of the upright position (Begbie, 1966).

Early Observations

Our ability to maintain balance is affected by visual information. This has been observed for some time in natural and not-so-natural situations.

An early field research note on the "haunted swing" illusion hints at the strong role of vision on posture. Wood (1895) described a fair ride in which one sat on a large swing (that held as many as 40 people) centered in a room furnished with among other items, a massive iron safe and a piano. The illusion was that the swing remained motionless except for a little jostling. In fact the room (with securely fastened furniture) actually swung around the stationary swing. Wood (1895, p. 227) describes his rides:

> ... each vibration of the swing caused those peculiar 'empty' sensations within which one feels in an elevator; and as we rushed backwards toward the top of the room there was a distinct feeling of 'leaning forward,' if I can so describe it - such as one always experiences in a backward swing, and an involuntary clutching at the seats to keep from being pitched out. We were then told to hold on tightly as the swing was going clear over, and sure enough, so it did, though the illusion was not so perfect as the high oscillations." Additionally, Wood relates: "the illusion was good, though the absence of centrifugal force, and the fact that the swing did not move with uniform acceleration as it descended, would indicate to a careful observer that he was not swinging freely. The curious and interesting feature however, was, that even though

> the action was fully understood, as it was in my case, it was impossible to quench the sensations of 'goneness within' with each apparent rush of the swing.

Wood (1895) also mentioned that as soon as he closed his eyes, the illusion vanished. Additionally, he stated that many people were made sick by the illusion (p. 227), "I have met a number of gentlemen who said they could scarcely walk out of the building from dizziness and nausea." Though Wood visited the ride several times, he could not suppress the 'goneness within'.

Wood (1895) brings up several pertinent points. First, a visual stimulus can override vestibular, mechanoreceptor, and even cognitive input. Wood had no sensation of movement with his eyes closed. Second, a visual stimulus alone can provoke motion sickness symptomatology. Finally, related to the last point, motion sickness appears to affect balance.

Helmholtz (1910) noticed the interaction of the visual and vestibular system though he did not identify the experience as this when he noted,

> In crossing a plank over a rapid little stream, one must be careful to avoid looking at the water so as not to lose his balance. When a person steps out on one of the lower ledges of the castle Laufen at the falls of the Rhine, and sees nothing before him but the mass of tumbling water, he has a tendency to fall over backward. (Volume III, p. 250)

Clinical neurologists have long noticed the stabilizing effect of vision on posture (see, e.g., Dichgans & Brandt, 1978). De Haan (1959) noted that a patient with bilateral labyrinthine function loss "must resort to the organ of vision" for maintaining equilibrium. The walk of an adult patient who has lost labyrinthine function was described as straddle-legged or even "the tottering gait of a drunk" as he enlarged his support surface. After some time, such a patient's gait returns to normal except in the dark.

Another common clinical observation is that when people who require refractive correction and have a several diopter change in prescription of their lenses, there is often a decrement in postural stability, nystagmus-like eye movements (oscillopsia), and/or nausea for a few minutes (but sometimes for hours and rarely for days) until they have had experience with the new magnifications of the retinal images. Once this habituation to the new magnification has occurred, removing and replacing the same glasses is no longer disorienting.

Early Experiments with Body Sway and Vision

An early series of experiments that studied the effects of practice, exercise, and visual cues on postural stability found vision to be of primary importance (Travis, 1945). Performance with normal vision in stationary surroundings was about three times as effective as when subjects were blindfolded. The earliest laboratory research on body sway that manipulated levels of visual information reported that body sway increased as the amount of visual information decreased, except in the case of blind subjects (Edwards, 1946). It was also noted that when subjects viewed an object in motion, such as a pendulum, their body sway increased.

Edwards (1946) also tested 72 subjects who were blind but with some amount of vision. The somewhat surprising finding with these subjects was that almost half of them swayed more with eyes open rather than eyes closed, in contrast to subjects who were "feebleminded, insane, deaf, and normal". Normal subjects swayed on the order of 50% more with eyes shut. In order to further study this result, normal subjects were given diminished vision conditions such as glasses distorted by five diopters and then covered with ink and paste. Under these conditions, decreased visual information led to increased body sway.

Another early paper also confirmed that decreased visual information led to increased body sway, and in addition, found that this relationship was preserved even on an unstable platform (Wapner, & Witkin, 1950). Interestingly, the researchers also found, that in a darkened room a "glow-in-the-dark" cube that rotated around a horizontal axis in front of the subject induced more sway than when the subject was blindfolded in the dark. The visual stimulus rolled +/- 40 deg from upright at a rate of 18 cycles per minute. As Edwards (1946) had found, visual motion increased sway.

Begbie (1966) studied the effects of alcohol and visual information on body sway. An unstable platform was used and subjects were tested with and without vision as well as with and without peripheral vision. In all cases alcohol increased sway. Eyes closed was also the least stable condition, conditions without peripheral input were somewhat more stable, and the condition of full visual input with information about body sway itself while viewed at the same time on an oscilloscope was the most stable.

De Wit (1972) also became interested in visual influence in body sway by an amusement ride, as had Wood (1895). In this particular circumstance the ride was a ship that appeared to list heavily. Actually there was no real list, instead all the items in the cabin were tilted with respect to gravity. People had no problem maintaining upright with eyes closed, but with eyes open, some people fell down.

De Wit then made further observations with subjects on a stabilogram. The subjects stood on the platform while watching a vertical light bar that moved slowly over an angle of 10° horizontally in both directions (1 cycle per 30 to 50 sec). Normal subjects showed a tendency to sway with the light bar. These findings are in support of Edwards (1946) who used a pendulum to influence body sway. Also, De Wit's subjects who were under the influence of diazepam

(Valium) swayed more than normals, which is similar to Begbie's (1966) finding that alcohol increased sway.

Visual Proprioception

Lee, Lishman, and Aronson are some of the most influential experimenters in the area of visual proprioception and body sway. Lee and colleagues were influenced by Wood (1895) and De Wit (1972), but primarily found Gibson's (1958, 1966) theories of vision-as-proprioception intriguing.

Gibson (1958) theorized about the proprioceptive nature of vision in the process of locomotion. In Gibson's 8th assumption on visually controlled locomotion and orientation in animals, he states:

> ... the eye is a device which registers the flow pattern of an optic array as well as the static pattern of an array. Conversely, such a family of continuous transformations is a stimulus for an eye. There are quite specific forms of continuous transformation, and the visual system can probably discriminate among them. This mode of optical stimulation is an invariable accompaniment of locomotor behavior and it therefore provides 'feedback' stimulation for the control and guidance of locomotor behavior. It might be called visual kinaesthesis. (p. 185)

With this assumption, Gibson seems to assert a largely unrecognized or ignored contribution to the sense of self motion. Gibson proceeds to give convincing argument about visual kinaesthesis functioning to provide proprioceptive feedback even though it contradicts Sherrington's earlier descriptions of proprioception (Sherrington, 1906 cited in Gibson, 1958). Kinaesthesis was defined by Sherrington, as the sense of bodily motion that depends on sensitivity of receptors in muscles and joints to compression, sensitivity of a statocyst to force, and sensitivity of the skin to deformation. Gibson's visual kinaesthesis depends on the sensitivity of a retinal mosaic to an overall change of pattern, an optical motion.

Gibson (1966) further claims that the only reliable information for locomotion is visual kinaesthesis. The sense of our own movement in the world is provided by the total motion of the optic array. Partial motion of the array indicates movement of an object in the world. Therefore, total motion of the optic array induces the perception of one's self being moved. Such is the case for the illusion of the haunted swing and this illusion of self-motion is now termed vection (Tschermak, 1931 cited in Dichgans & Brandt, 1978). Vection may also be experienced outside the laboratory and fairgrounds. For example, it is not uncommon for a driver to "stomp" the brake at a traffic light as another car slowly rolls forward into peripheral view, because the driver has the illusion of rolling backward.

Visual kinaesthesis or visual flow theory as it later became known was not tested with body sway until Lee and colleagues began experimentation in the 1970s. They proceeded to collect data in a series of experiments that support the theory of vision as an autonomous kinaesthetic sense (Lishman & Lee, 1973; Lee & Aronson, 1974; Lee & Lishman, 1975). In fact, these researchers were able to show elegantly that vision plays an important (they assert, a dominant) proprioceptive role in balance using body sway as a dependent measure. These studies all used a very important piece of equipment that seems to have been inspired by Wood (1895). The apparatus was a "swinging room" that moved linearly (not rotating around the horizontal axis) past the subjects, and its direction and speed could be controlled. These researchers used this room to demonstrate dramatically that in cases of conflict, visual information can dominate control of body sway.

Subjects stood on a stationary floor facing the closed end of the room. In the first study (Lishman & Lee, 1973), subjects were asked to report on their own movement and that of the room as they were standing still. Subjects reported themselves to be moving, not the room itself, when the room moved. This illusion is a linear form of vection. In the cases when the subject was standing on a fixed floor, controlling movement of the room around herself, there was still strong visual dominance despite the added mechanical and cognitive information. The experimenters reported (p. 294): "Finally, we ourselves are still visually dominated despite having intimate knowledge of the apparatus and being subjects for many hours."

Another important observation in this first experiment was that subjects standing on the stationary floor, swayed in synchrony with the room movement. It was asserted that visual information about body movement is used in maintaining balance. In accordance with Wood's (1895) earlier observations, many subjects reported dizziness and motion sickness.

In the second reported study (Lee & Aronson, 1974), infants were studied in the moving room in order to determine how visual proprioception is expressed in the early stages of development of postural control. The infant subjects (aged 13 to 16 months) were videotaped as they stood facing the closed end of the moving room (as had adult subjects in the previous experiment). The room was moved linearly away from the infant on one trial and toward the infant on the next trial. Eighty-two percent of the responses [sway (26%), stagger (23%), or fall (33%)] were in the direction that the room was moved. It can be inferred that the infants were making compensatory adjustments in accordance with the visual information produced by the room motion. The effect of the room motion on balance was more pronounced in infants than in adults. This implies that when an infant is learning to stand, she relies most heavily on visual information.

Butterworth and Hicks (1977) compared postural stability in two groups of infants. The older group was

15.8 months old on average and could stand without assistance. The younger group was 10.9 months old on average and could sit unassisted but could not stand. These investigators wanted to determine more definitively whether vision becomes proprioceptive as infants learn to stand, or if postures that occur earlier in development than standing are also under visual proprioceptive control. Infants were videotaped and scored positive if they responded in the direction the room moved, as in the comparison study (Lee & Aronson, 1974). Subjects were seated facing an end or a side wall and the results were as follows: 72.1% of older infants responded positively for fore-aft movements and 48.5% responded positively for lateral movements; 90.8% of younger infants responded positively for fore-aft movements, and 60.8% responded positively for lateral movements.

These experiments support Lee and Aronson's (1974) findings of visual proprioceptive dominance in infants and extend their conclusions. The proprioceptive nature of vision appears to function earlier than the ability to stand because the discrepancy of a stationary floor and moving walls elicited responses in infants who had not yet learned to stand unassisted. Additionally, lateral movements affected balance although not as much as fore-aft movements of the room.

Now, the third reported set of experiments in the series of Lishman and Lee (1975) will be reported. In this study, different stances were examined in order to more closely examine the visual role of postural control. A "sway meter" recorded the capacitance between the subject's back and a small charged plate about 20 cm from the subject. Capacitance change as the subject moved was converted to voltage, which was assumed linear over a range of 5-60 cm. This voltage was differentiated to give sway velocity. A circuit (presumably a rectifier) took the absolute value of sway and integrated this over 10 seconds. Velocity and 10 sec time averages were plotted with a pen recorder. Subjects either stood normally, on a 25° ramp, on a compliant surface of foam pads, or stood on their toes, while viewing a stationary room, the room moving sinusoidally, or the room moving irregularly. Vision improved balance for all four stances when the stationary room was seen versus eyes shut. The sinusoidally moving room induced sinusoidal motion of the subject's trunk, and the irregularly moving room induced sways roughly as large as observed with eyes shut. This lends support to the researchers' hypothesis that all the proprioceptive information required for balance is potentially available visually. Misleading visual information could not be ignored.

For their next experiment, Lishman and Lee (1975) picked three more stances that were less familiar and had poorer mechanical proprioception. They called these "stances impossible without visual proprioception". In the first stance, the subject wore shoes and stood on her insteps on a narrow transverse beam. This stance increased the possible angle of inclination of the foot and also decreased the foot support base. The second stance was called the "Chaplin" stance, in which the subject stood with her heels together and feet out in a perfect line a la Charlie Chaplin or the first position in ballet. This position changed the pattern of muscle movements that control lateral and fore-aft sway. In the third stance, the subjects stood on one leg with the contralateral foot behind their calf and with their contralateral arm extended sideways holding a weight. This stance changed the mechanical proprioceptive feedback as well as the support base and the equilibrium angle at the ankle.

These stances were timed for 30 sec each with eyes open and with eyes shut. A video camera recorded the subjects' ankle positions and the room as it moved. With eyes open, all 10 subjects were able to balance for the full 30 sec in all stances. After some practice with eyes shut subjects could maintain the balance beam stance for 5 sec, the Chaplin stance for 7 sec, and the one-legged weighted arm stance for 15 sec. When the subjects were in the moving room with eyes open in these stances, the misleading visual information caused them to sway or fall with the room's direction over 80% of the time. The researchers likened a subject to, " a visual puppet; his balance can be manipulated by simply moving his surroundings, without his being aware of it" (Lishman & Lee, 1975, p. 94).

In the last two experiments, Lishman and Lee (1975) made a change in room decor. In all the experiments there had been some visual cues in the room to make the illusion more compelling, such as ceiling lights and posters on the side walls. This time, centered in front of the subject was the addition of a rigid mesh cylinder 47 cm in height and 28 cm in diameter. The distance from the subject to the near part of this cylinder was 30 cm, plus or minus 4 cm when the room moved away from or toward the subject. This cylinder, made of 13 mm wire mesh, may have given ambiguous cues for binocular convergence that may, in turn, have affected body sway.

Vection-related studies of body sway

Concurrent with the Lee series of investigations were investigations carried out by Dichgans and colleagues (Mauritz, Dichgans, Allum, & Brandt, 1975; Dichgans, Mauritz, Allum, & Brandt, 1975). Data was collected from force platforms and Fourier analysis conducted to give the frequency spectrum of the output. Rather than examining vision as a proprioceptive sense (Gibson, 1958; 1966; Lishman & Lee, 1973; Lee & Aronson, 1974; Lee & Lishman, 1975), an engineering approach was used to describe balance maintenance. A multi-loop control system was assumed with the control inputs being: vision, vestibular otoliths, semicircular canals, and muscle and joint proprioceptors. In order to study the influence of each of the control inputs, Dichgans et al. (1975) and Mauritz et al. (1975) compared the power spectra of sway of normals to normals without stimulation of certain of the inputs, as well as the power spectra of sway in patients with isolated lesions of the vestibular, cerebellar, and the somatosensory proprioceptive system (such as a _tabes dorsalis_ patient).

In order to disrupt visual inputs, the researchers had subjects stand in front of a hemispherical dome rotating about a horizontal axis (roll) whose inner surface was covered by randomly distributed colored circular patches of different size on a white background. As in the previous studies, body sway was found to increase when eyes were closed (the condition to remove visual input altogether). The moving visual scene on the dome gave a strong sense of body rotation (roll vection) and was very destabilizing.

For ten vestibular patients who were tested, Dichgans, et al. (1975) found no simple correlation between the side of the deficiency in the subjects with vestibular lesions and the direction of average deviation of posture. Also, there was not a characteristic difference of the Fourier spectrum shown by these patients with respect to the spectra of normals. In six patients with slowly progressing cerebellar atrophy, the sway amplitude generally was much larger than the normal range particularly in the fore-aft direction with distinct peak characteristics in the power spectrum. The data on one tabes dorsalis subject was characteristically different from the power spectra of the cerebellar subjects, but the subject did not exhibit greater instability. Both Dichgans et al. (1975) and Mauritz et al. (1975) found that subjects with motion sickness symptoms from viewing the rotating dome were less stable than non-sick subjects.

Another study using a type of vection to examine the relationship of postural equilibrium and vision caused three (ten percent) of the subjects to faint (Lestienne, Soechting, & Berthoz, 1977). These researchers also collected data from a force platform and were interested in the study of visually-induced linear vection. Thirty subjects were provided an "optic tunnel" by wearing a set of angled mirrors in front of the face that captured moving visual scenes from an overhead screen on which the scenes were projected. Most of the peripheral and foveal fields of vision were filled with the images (a checkerboard pattern), thus the term "optic tunnel".

Lestienne et al. (1977) observed that 80% of subjects showed clear postural readjustment from the motion of the visual scene. The change in fore-aft direction (pitch) was always in the same direction as the image motion whether it was located peripherally or centrally or restricted to the upper or lower half of the visual field. The 20% of subjects who showed little or no postural readjustment were given a mental arithmetic task (mental arithmetic has been used traditionally in caloric testing to enhance nystagmus). Having subjects perform mental arithmetic produced the postural response in 4 of the 6 initially unresponsive subjects.

Power spectra of the forces exerted on the stabilometer platform were calculated for each trial. The power spectrum while viewing stationary visual fields was largest below 0.1 - 0.15 Hz and had a broad peak at low frequencies which varied from trial to trial. At frequencies above about 0.15 Hz, the power spectrum decreased by about 20 dB per decade. Moving the visual field produced two effects. First, the amplitudes of body sway increased at the low frequencies. Second, several sharp peaks appeared in the sway power spectrum between 0.15 and 0.5 Hz. The amplitude of these varied from subject to subject. No consistent relationship between the amplitude of sway oscillations and stimulus parameters (such as image velocity or spatial frequency of the pattern) could be determined. Fore-aft sway lagged the image motion and this lag increased as the image motion frequency increased. Either eyes closed or viewing the moving visual scene (which conflicted with vestibular and proprioceptive cues) were roughly equivalent for the amount of sway that was induced; the body sway was increased by about 50% from eyes open and viewing a stationary scene.

Miyoshi, Shirato, and Hiwatashi (1979) found similar disturbances of balance with high velocity vection stimulation. These researchers studied body sway in response to a large white cylinder with black stripes (optokinetic drum) rotating around a vertical axis at various speeds and accelerating in various fashions. This type of stimulation typically produces rotary vection. Similar to Lestienne et al. (1977), were findings that extreme velocities made it impossible for subjects to stand in one position (though none were reported to have fainted).

Saccadic eye movements and efference copy theory

At this point in the literature, researchers are beginning to examine more closely the particular elements of the visual system that influences body sway, such as, saccades, retinal image motion, and binocular cues. Hypotheses concerning visual flow (an extension of Gibson's theory), efference copy, and hierarchical organization of sensory inputs were proposed and tested to account for effects of vision on body sway.

Iwase, Uchida, Hashimoto, Suzuki, Takegami, and Yamamoto (1979) were not so much interested in the particular effects of visual stimuli on postural stability, but the effects of eye movements on stability. Iwase et al. (1979) measured fore-aft body sway along with vertical and horizontal electro-oculograms (EOG's). Subjects were tested in the dark and a target was used to guide periodic saccades in vertical and horizontal directions. The occurrence of saccadic eye movements stabilized fore-aft body sway when the frequency of saccades was between 0.2 - 1.0 Hz, and when the amplitude of the saccade was between 5° - 40°. The authors disproved the idea that the stabilization was due to presence of the target image by showing that volitional saccades either in the dark or with eyes closed also reduced the fore-aft body sway. These authors suggest that at the initiation of saccadic eye movements the spinal reflex systems may also be influenced.

Another experiment that examined saccadic eye movements, body sway, and the efference copy theory had findings similar to those of Iwase et al. (1979). White, Post, and Leibowitz (1980) compared body sway during saccadic eye movements to body sway when the visual surround was moved in a motion similar to a saccade and viewed with the stationary eye. Subjects stood in front of a large grating pattern of gray and white vertical stripes. Mounted near the center were two lights separated by 4° horizontally. Subjects were to fixate whichever light was illuminated. Voluntary saccades were directed by illuminating the lights alternately.

In order to produce a similar movement of the surround, the grating pattern moved horizontally through 4° of arc in

33 msec. For testing, subjects stood on a force platform on one leg. These researchers found that the saccadic eye movements did not increase body sway. However, they did not find that body sway decreased as had been found by Iwase et al. (1979).

There was a different methodology between the studies with respect to stance. White et al. (1980) were attempting to increase lateral sway by having the subjects stand on one leg. Body sway dramatically increased when motion of the visual surround mimicked a saccade. Like Iwase et al. (1979), these researchers concluded that at the initiation of a saccade information is relayed in the nervous system to cancel/counteract/ignore as false feedback the retinal image motion that occurs. These experimental findings lend some support to the efference copy theory. This theory proposes that knowledge of intended movements is used in an internal reference of self orientation. This reference may be used to distinguish between movements of self relative to surroundings and movements of surroundings relative to self.

Hierarchical organization of sensory inputs

Vestibular emphasis.

Nashner, Black, and Wall (1982) were also interested in efference copy theory but believed the theory inadequate by itself to explain the context-dependent changes in the weighting of inputs to the equilibrium control system. The inadequacy they point to is that shifts in body orientation may occur without prior knowledge due to the inherently unstable characteristics of the body, an unstable support surface, or unforeseen external perturbations. Nashner et al. (1982) followed a research paradigm similar to the clinical work of Mauritz et al. (1975) and Dichgans et al. (1975).

Nashner et al. (1982) examined patients with vestibular deficits in order to establish the influence of the vestibular system in the control of posture. Twelve patients were accepted with the criteria that they: (1) had no other central nervous system disorders, (2) could stand and walk without assistance, (3) were not experiencing spontaneous vertigo, and (4) maintained a lifestyle as normal as possible. The patients fell into three clinical categories: one patient with complete loss of vestibular function; five patients with significant disruption of vestibular function; and six patients who were very mildly afflicted. There were also two age-matched normal subjects, and a pre-existing data base of comparable results from younger normal subjects.

Nashner et al. (1982) used a testing platform with a moving support surface for each foot. These stabilometer surfaces could be fixed, translated, or "stabilized" with respect to body movements. Each surface independently translated horizontally or vertically, and rotationally about the axis of the ankle joints. For the stabilized condition the support surfaces rotated in proportion to the fore-aft sway motions of the body, as determined by a potentiometer attached to the subject's hips by a lightweight rod. The visual surround could likewise be used to induce image stabilization by continuously moving the visual surround in proportion to the measured fore-aft sway. For the surface and visual stabilization conditions to accomplish their objective, it was necessary to assume that the body sways like a rigid inverted pendulum, ignoring the knees, lateral sways, and other possible influences.

The potentiometer attached to the subjects' hip had the steady state offset removed, the signal was rectified and integrated, and was then scaled to be a fraction of the maximum fore-aft sway amplitude possible (approximately 8° forward to 4° backward) to provide a performance ratio. A performance ratio of 1.0 was assigned when the patient grabbed the handrail, took a step, or had to be supported by an assistant.

Nashner et al. (1982) found for all subjects standing on a fixed platform the performance ratios were less than 0.3 and degraded slightly (statistical analyses were not provided) as they were measured with eyes open, eyes closed, and finally with a "stabilized visual image." For the conditions where the platform moved with the subject, the findings were the most dramatic. In the eyes open condition, the patient with complete loss of vestibular function received a performance ratio of 1.0 because of the inability to stand. In the eyes closed condition, the same patient again could not stand and neither could one patient from the significantly disrupted category. In the "stabilized visual image" condition, 6 of the 12 patients (including the two mentioned previously) could not stand.

Based on these findings, Nashner et al. (1982) develop the argument that vestibular inputs play key roles in a hierarchically organized system for equilibrium control. On a low hierarchical level, the weighted sum from the vestibular system, proprioceptive systems involved in reacting to support surfaces, and vision has a direct impact on the activity of the muscles involved in postural control. On a higher hierarchical level, the vestibular inputs provide the orientational reference by which conflicts in support surface proprioception and visual orientation may be resolved. Vestibular patients were able to stand in all conditions except the condition which introduced the most conflict, which was "stabilized support surface" (platform moved with the subject) and "stabilized visual image" (visual surround moved with the subject). In contrast, normal subjects performed well when exposed to all conditions. This suggests that the abnormality of patients was not so much the loss of direct vestibular inputs to posture, but the inability to suppress quickly the conflicting support surface proprioception and visual inputs.

Forssberg and Nashner (1982) used the same equipment and protocol described above to test children who ranged in age from 1.5 to 10 years of age. Seventeen children were selected who were capable of standing and walking without support and had no history of neurologic or developmental disorder. The children were divided into four age groups: four 1.5 - 3.5 years; four 3.5 - 5 years; six 5 - 7.5 years; three 7.5 - 10 years. The primary findings were that the postural adjustments of all the children were similar to those of adults although they tended to be more variable. Young children were able to stand on the "stabilized support surface" with their eyes closed. However, children younger than 7 to 8 years old lost their balance when presented the condition of "stabilized support surface" and "stabilized visual image."

This last finding was interpreted as lack of development of the hierarchically higher-level process described above. The higher variability in responses in younger subjects was interpreted as underdeveloped adaptive mechanisms which could also be related to higher level processing. The findings also support the low and high level hierarchical organization theory because children exhibited relatively well-developed postural control but they were less able to adapt to changes in environment.

Proprioceptive emphasis. Many of the vection experiments cited above (Lee & Lishman, 1975; Lestienne et al. 1977) show little or no habituation with adult subjects. Bronstein (1986) argued that this implies an inflexible visual control of posture.

To study habituation, subjects were tested on a stationary force platform located within a moving room (similar to that of Lee & Lishman, 1975) which had wall coverings of red and pink checkered material. There were nine normal subjects, one patient with no proprioception below the knees due to tabes dorsalis, and one patient with acquired absence of vestibular function. Subjects faced a lateral wall for testing first, shoeless on the platform and next, standing on two pieces of foam to reduce proprioceptive cues.

Bronstein found for normal subjects that the first linear movement of the visual surround initiates a postural displacement in the direction of the stimulus (primary component), followed shortly afterwards by a corrective (secondary) displacement in the opposite direction. The primary component was almost completely suppressed on subsequent movements of the visual surround when subjects stood shoeless on the platform. When later standing on foam, the amplitude of the primary component was considerably larger and it was attenuated only minimally during the subsequent stimulus movements.

The tabes dorsalis patient swayed markedly in the direction of room movement with no effective secondary (corrective) component present. This resulted in repeated falls off the platform (he was caught by two observers). The patient without vestibular function was able to perform the task even when standing on foam and the primary component was suppressed on subsequent presentations of stimulus motion. These findings suggest that in the absence of reliable visual information, proprioceptive cues can take precedence over vestibular cues.

The performance of Bronstein's (1986) patient without vestibular function seems to be at odds with that of Nashner's patient without vestibular function (Nashner et al., 1982). However, direct comparison across the experiments is problematic because of the lack of standard measures for postural stability and body sway and the lack of statistical analyses.

Visual emphasis. Some characteristics of visual stimuli were investigated for their role in stabilization of posture by Paulus, Straube, and Brandt (1984). These investigators support a more dominant role for vision in postural control than did Nashner et al. (1982), Forssberg and Nashner (1982), or Bronstein (1986). These researchers (Paulus et al., 1984, p. 1144) suggest that:

> Unlike vestibular stimuli, which invariably lead to the sensation of body motion (and therefore require a postural reaction in order to maintain balance), visual stimuli provide for two perceptual interpretations: either self-motion or object-motion. The decisive visual signal that starts active postural correction of body tilt may be dependent either upon relative image shift on

> the retina of the stationary visual surroundings or on 'efferent motion perception' when fixating stationary targets.

A vestibular stimulus can be defined by amplitude, duration, and direction of body acceleration. Variability of visual motion stimuli make them more complex to define. Factors involved include: optical focus/visual acuity; the number, location and size of stimuli in the visual field; and changes in eye-target distance, all of which are related to changes in retinal velocities. The Paulus et al. (1984) study investigated how these factors affect body sway in their experiments 1, 2, 3, and 5.

Subjects' sways were measured on a stabilometer for one minute per condition. The stabilometer outputs were band-pass filtered between 0.09 and 40 Hz, and root mean square calculated for subsequent analysis. Subjects in a standard eyes open condition stood in front of a flat screen 100 cm from the eyes. The screen was covered with randomly placed colored dots ranging in size from .05 to 1 cm diameter.

The purpose of their fourth experiment was to examine the relationship between continuous and discrete visual input, and body sway. Paulus et al. (1984) noted that White et al. (1980) found that saccades did not affect body sway, which seems to support the theory that continuous visual input is not necessary to maintain balance. An 8 Hz flicker frequency increased sway approximately 30 per cent. Flicker frequencies of 1, 2, and 4 Hz all increased sway approximately 60 per cent. These findings suggest continuous motion of the retinal image effectively stabilizes body sway, but it is not a necessary precondition.

There is clinical relevance of these findings in regard to acquired ocular oscillations such as nystagmus. These oscillations might impair the mechanism of continuous motion perception, and might cause misleading motion input that would affect postural control. Acquired involuntary ocular oscillations may not always have an accurate efference copy signal; this in turn may explain oscillopsia and pathological body sway even without voluntary head or eye movements (Paulus et al., 1984).

Visual flow theory

A series of experiments by Stoffregen (1985, 1986) supports the finding of Paulus et al. (1985) that both central and peripheral retinal information is important to controlling body sway. Stoffregen (1985, 1986) draws on Gibson (1958) to test the visual flow theory, with respect to the proprioceptive information from vision as one walks through the world.

Stoffregen (1985, 1986) studied two different optic flow patterns as they fell on different eccentricities of the retina. If a person looks in the direction of any linear motion, the optical flow expands radially outward from the point toward which one moves, sweeps laterally past, and converges behind the viewer. In this flow pattern there are different local structures. Stoffregen (1986) uses the example of the lines of longitude on a globe. These lines converge at the poles and are parallel at the equator. For the optic flow pattern, as the viewer nears the line of motion, the flow pattern is predominantly radial; and as the optic flow sweeps past the viewer, the flow pattern is predominantly parallel (also referred to as lamellar).

A moving room was used that was quite similar to the moving room used by Lee and Lishman (1975) to provide visual stimulation. Subjects stood in two orientations, facing the back wall as it moved toward them, or facing a side wall as it moved past. By restricting the subjects' field of view either centrally or peripherally, Stoffregen (1985, 1986) found that the central areas of the retina are sensitive to both radial and parallel optical flow patterns. The retinal periphery is definitely capable of detecting sway-related information in a lamellar structured flow, but it is not clear that the periphery responds as well to radial flow patterns.

University of Florida experiments

A series of experiments conducted at the Psychology Department at the University of Florida also studied the effects of particular visual stimuli on body sway. An acoustical head-tracking system was used for measuring body sway in this series and the latest version of this system used in the present study will be discussed in the Methods chapter below.

The first experiment was an extension of the visual saccade and body sway research conducted by White, et. al, 1980. Krantz (1985) used a large semi-cylindrical screen that had vertical gratings projected onto it. The projection was created by passing a light produced by a thin vertical filament through a slotted can. By rotating the can with a galvanometer, stimulus surround motions were produced. The stimulus surround motions were necessary to simulate saccadic eye movements. Subjects were tested while standing on one foot in order to reduce proprioceptive feedback. Body sway was indexed by head movements that were measured by four microphones that received acoustical signals from a lightweight (3 oz.) device that the subjects wore on their heads. As a subject swayed, the acoustical signals arrived at each microphone with characteristic timing relationships. Body sway was measured for the x, y, and z translational axes. For each axis a Fast Fourier Transform analysis was performed to compare the power spectra in each axis in response to particular stimuli.

Krantz (1985) examined six different extents of saccades and found in support of White et al., (1980) that sway was suppressed during actual saccades but not during the simulated saccades. In addition, Krantz found that sway suppression was greatest during small actual saccades, this finding was in opposition to the trend found psychophysically that suppression increases as saccade size does.

Krantz (1988) also examined body sway when motion in the surround was introduced that was manipulated to occur during a saccade. Body sway was found to be suppressed under these conditions in addition to the suppression of sway found when the surround was still during saccades (Krantz, 1985).

In the second experimental series, Woods (1986) examined the effects of varied visual feedback on body sway in hopes of clarifying the relationship found by Edwards (1946) which was, "... increasing interference with vision is accompanied by relatively increased amounts of sway in the human body." Subjects again were tested while standing on one foot in the following conditions: (1) eyes open viewing a stationary, full-field, high-contrast stimulus surround; (2) eyes open viewing random visual field motion that results in incorrect body sway feedback; (3) eyes open viewing a stabilized visual field that results in incorrect feedback of no body sway; (4) eyes open while wearing opaque goggles so surroundings were invisible; (5) eyes open while wearing diffusing goggles so surroundings were luminous but contourless; (6) eyes closed. The findings indicated increasing sway for these conditions in this order. There were significant differences in overall sway between all conditions except conditions four and five. Spectral analysis indicated sway was predominantly low frequency which is consistent with the literature, up to 98% of the power is present at frequencies less than 1.0 Hz. Spectral signatures associated with specific conditions could be reliably distinguished.

Further study comparing eye closure and eyes open in darkness found that postural stability and vestibular ocular reflex (VOR) strength declines significantly when the eyes close, whether or not the retina remains illuminated (White, Woods, & Post, 1989). In this study the retina was illuminated by a light source held in the subject's mouth while she wore opaque goggles.

In the third series of experiments, Shuman (1987; Shuman & White, 1988) examined the effects of altering the relationship between a subject's movement and the resulting retinal image motion (visual feedback) on body sway. Based on findings of increased body sway with a "stabilized image" (a visual surround which tracked the fore-aft motion of a subject's head in an attempt to eliminate the visual sense of motion) from Nashner et al., (1982), Shuman looked more closely at altering visual feedback. Of specific interest was the size of retinal image motion and how this correlated with sway. An interesting observation brought up by Shuman (1987) is that changes in prescription lenses also changes the relative retinal image motions.

The visual display system described above was used to manipulate visual feedback. Feedback from a subject's own head movements was used to drive a galvanometer which controlled the projected vertical gratings with the amount of gain desired in the visual feedback to the subject. A stimulus gain of +1 results in the stimulus following along with the subject's head movements and thereby creating a "stabilized" retinal image. Under normal viewing conditions, when a person moves their head, the visual field is moved the same amount in the opposite direction. The 8 stimulus feedback gains used were positive and negative 2, 1.5, 1, and 0.5.

Shuman (1987) did have anecdotal reports of motion sickness with his stimuli. A significant body sway gain, different from baseline, for the positive and negative feedback conditions was found. The lateral sway most clearly showed body sway gain spectra arranged in direct order with positive stimulus feedback gains and in inverse order with negative stimulus feedback gains. The sway spectra for positive and negative feedback also differed qualitatively from each other. When the deceptive feedback was positive, it was observed that body movements tended to continue relatively unopposed up to a point, with an acceleration that varies directly with the feedback gain. Eventually, a compensatory reaction was necessary to prevent falling. When the deceptive stimulus feedback was negative, it was expected that greater feedback should result in greater than normal opposition to body movements. This was not observed, but may have resulted from feedback delay in the equipment. In summary, greater positive feedback leads to decreased stability and greater negative feedback is expected to lead to increased stability.

A study on walking down stairs had similar findings (Craik, Cozzens, & Freedman, 1982). As subjects descended steps, if the visual surround moved downward as subjects descended EMG activity was significantly different compared to the surround not moving. (This is like Shuman's positive stimulus feedback in that the stimulus moved with the subject.) If the visual surround moved upward as they descended there was no difference in EMG compared to when there was no movement of the surround. This was like Shuman's negative stimulus feedback, and it also could not be shown to increase stability by Craik et al. (1982).

Applying Shuman's results to the example of the corrective lenses, those people who are acclimatized to their lenses are relatively stable with or without them, but are destabilized temporarily with a new prescription. Perhaps experience enables recalculation for the magnitude of expected movements of the retinal images to match the requirements of changing optical status.

Shuman describes a model for a hierarchy of postural control that is similar to Nashner but with some additional information. Shuman suggests that absolute retinal image motion predominantly affects the extent of body movement while changes in relative motion apparently increase or decrease particular frequency components in the body movement spectra. The sensitivity to absolute movement may be relatively independent of the external context and serve as a directional reference. Sensitivity to relative movement conveys vector magnitude information and may be very dependent on the full 3-D composition of the external environment as well as accurate perception of those characteristics by the visual system.

Binocular vision and body sway

Fox (1990) was interested in a more general model of visual spatial orientation than the efference copy theory (White, et. al, 1980) and the visual flow theory (Gibson, 1958; Stoffregen, 1985, 1986). He believed both theories can account for most of the data on visual control of postural equilibrium but that neither is sufficient to explain the data. Fox did not believe that the efference copy theory permitted specific predictions for direct tests, but that the visual flow theory allowed specific predictions regarding self-motion perception.

Visual flow theory contains a proprio-specific component determined through the observer's position, orientation, and movement, relative to the environment. An example of a proprio-specific pattern is motion parallax.

The visual information available in these types of proprio-specific patterns is available to both binocular and monocular vision, in principle. Fox's (1990) first two experiments compared monocular and binocular viewing. Test conditions were: eyes closed; full illumination; single target (a fixation point); motion parallax (3 target lights aligned in depth provided information for lateral body sway); expansion-contraction (3 target lights aligned in the fronto-parallel plane provided information for fore-aft sway); and expansion-contraction plus motion parallax (3 target lights aligned as a diagonal in depth provided information for lateral and fore-aft sway simultaneously).

In the first study there were no systematic differences between monocular and binocular fixation for lateral sway but there were differences for fore-aft sway. This study was run again, this time with subjects standing with feet placed heel to toe instead of side by side; this stance increased overall sway. Except for eyes closed there was greater sway in all conditions for monocular fixation than for binocular.

The third experiment was run this time using fully structured visual fields. The conditions were: binocular in light, binocular in dark; monocular in light, monocular in dark; eyes closed in lighted room, eyes closed in dark room. There was a complex interaction of foot position, eye-target distance, and binocularity again suggesting that simple optical/retinal explanations are insufficient to explain visual control of postural equilibrium. Binocular as opposed to monocular fixation resulted in decreased body sway for both fore-aft and lateral sway even when the observer was in complete darkness. This suggests that the stabilizing effect of binocular fixation is not mediated primarily by stereopsis or other retinal activity; if it were, there would be no difference between binocular and monocular fixation in the dark, where there appears to be no meaningful retinal stimulation in terms of retinal displacement. White et al., (1989) and Woods (1986) had found differences between eye closure and eyes open in complete darkness.

The consistent difference with all 3 experiments of binocular vision decreasing body sway as compared to monocular vision is a problem for both visual flow and efference copy theories (Fox, 1990). Information in the visual flow field is, potentially, equally useful to both monocular and binocular vision. Traditional efference copy theory cannot explain this difference, unless independent reference signals for each eye are postulated.

Fox suggests that there may be several visual causes for the monocular/binocular difference. One source of visual information is stereopsis, which specifies, for a given object, a single 3-D spatial coordinate relative to the point of binocular fixation. A second related, source of visual information is primarily oculomotor (vergence). To the extent that visual control of body sway is a spatial orientation task, stereopsis and vergence inputs may be critical sources of information for the postural control mechanism.

Another study on postural stability and binocular depth cues was conducted by Lasley, Hamer, Dister, and Cohn (1991). Lasley, et. al, (1991) were specifically interested in the effects of stereo-ambiguous stimuli like those provided by an escalator tread. They hypothesized that if this type of stimulation increases instability (measured by body sway), it could be involved with falls on escalators.

Stereo-ambiguous stimuli may cause disorientation because such stimuli permit false fusion (which is a stable but inappropriate angle of visual convergence). A familiar example of stereo-ambiguous stimuli is like that found in "the wallpaper illusion", first described by Meyer (1841, cited in Lasley et al., 1991). This illusion occurs when a person with normal binocular vision views a pattern that is periodic in the horizontal meridian of the visual field. When viewing such a pattern, the two eyes may adopt an angle of convergence that is inappropriate to the actual distance of the object, but which because of the periodicity of the pattern, allows fusion to take place. If this occurs, the object may appear to be substantially closer to (or farther from) the viewer than its objective distance. Binocular and monocular depth cues are not in accord in such a case and disorientation is commonly reported.

Nine subjects viewed vertical stripes of 1.23 cycles per degree, the control condition was the same except for the addition of five superimposed black letter patterns whose presence was intended to prevent false fusion. The control pattern would give cues of diplopia or double images which would be readily perceived.

The striped pattern without the superimposed control targets, increased the variance of the fore-aft sway which was predicted by the hypothesis of stereo-ambiguity. Six of the nine subjects showed individual effects in the predicted direction, although the effects were generally less than a factor of two. The pooled results from all subjects showed a statistically significant increase in postural instability (mean squared deviation from the mean position or variance) when viewing the test pattern. This was the first demonstration that a stationary visible stimulus could increase sway when there was no optical distortion or other stimulus degradation.

Field tests on 12 subjects were conducted with stationary unoccupied escalators. One escalator in its normal condition, and the other one painted with a non-periodic logo at the center and white paint in the grooves to lower cleat-groove contrast. Subjects stood on the sway transducer located at the bottom of the platform. The results showed significantly less sway variance, by a factor of two for the pooled data, for the painted escalator than for the unpainted escalator.

Motion Sickness

Background

Motion sickness (recently reviewed by Benson, 1984) is the normal response of a healthy individual, without organic or functional disorder, from exposure to unfamiliar motion of sufficient intensity and duration. If the provocative motion is severe, then the absence rather than the presence of symptoms is abnormal. Historically, the vestibular system has been assumed to be a major contributor to motion sickness. Irwin (1881, cited in Tyler & Bard, 1949) and Palasne de Champeaux (1881, cited in Tyler & Bard, 1949) were credited with being the first investigators to suggest that seasickness was caused by stimulation of the labyrinths because of the similarity between seasickness and Meniere's disease. William James (1882, cited in Tyler & Bard, 1949) was unable to induce dizziness by rotation in almost one-third of 519 subjects that were affected by acquired "deaf-mutism". Also, a study of labyrinthine-defective individuals (caused by vestibular lesion) with otherwise intact nervous systems did not experience motion sickness (Kennedy, Graybiel, McDonough, & Beckwith, 1968). Moving visual patterns may induce motion sickness, but the vestibular system may still be involved because of its interactions with the visual system. Interestingly, labrynthine-defectives have been shown to experience vection induced from optokinetic displays without experiencing motion sickness (Cheung, Howard, Nedzelski, & Landolt, 1989), suggesting that the visual-vestibular interaction may remain intact.

Motion sickness may strike on any conveyance from camels to spacecraft. It is prevalent among passengers of cars, boats, planes, and even flight simulators and virtual realities elicit nausea. Motion sickness has been reported throughout history and there is a wide range of individual differences. The symptoms of motion sickness include but are not limited to: sweating, pallor, drowsiness, alteration of respiratory rhythm with sighing and yawning (sometimes known as sopite syndrome (Graybiel & Knepton, 1976)), headache, eye fatigue, dizziness, nausea, and vomiting.

In situations where there is continued exposure to provocative motion, as on a ship, adaptation typically occurs for all individuals although the time course may be variable. Usually by day four, all symptoms are gone. However, on return to a stationary environment there may be a motion sickness-like response as the body readapts. The term mal de debarquement is given to the illness experienced by sailors upon return to land.

The protective adaptation may be progressively lost if the exposure to the provocative motion ends. Also, it has long been observed that adaptation to motion sickness is case specific. Erasmus Darwin (1801, cited in Benson, 1984) (whose grandson suffered so greatly from the motions of the 'Beagle') described sailors, who had grown accustomed to the motion of a large ship, becoming sick when they transferred to a row boat.

There are individual differences in susceptibility to motion sickness and there is anecdotal evidence of ethnic differences, as illustrated by the following quote from Paul Theroux (1993, p. 37):

> In Polynesia, I rarely met anyone who did not claim to get horribly seasick on a boat, no matter how short the trip. Even on the brief inter-island ferry rides this race of ancient mariners puked their guts out.

Robert Stern has investigated the higher incidence of motion sickness in Chinese subjects than European- or African-Americans (Stern, Hu, LeBlanc, & Koch, 1993). The Chinese group of subjects reported significantly more nausea and other symptoms of motion sickness than either of the other two groups (who did not differ significantly from each other).

Motion sickness is a serious concern in the aerospace industry. The illness may interfere with vehicular control, not only by the act of vomiting, but also by debilitating the operator who may become so apathetic and depressed that performance is seriously degraded (Benson, 1990).

Theories

There are several theories about why motion sickness occurs. One is the evolutionary theory (Triesman, 1977) which hypothesizes that the body responds erroneously to a disturbing environment in the same way it would respond to an ingested poison, by vomiting. Treisman states that many toxins have early effects on the vestibular system. A poisoned vestibular system giving unreliable motion signals, could cause one to vomit and become otherwise autonomically aroused.

The most prevalent theory is known as the neural mismatch or sensory conflict theory. This theory states that the cause of motion sickness is due to conflicts between the senses. This theory was suggested by Irwin (1881, cited in Benson, 1984) who also coined the term "motion sickness". Sensory conflict theory has been extended over the years to include conflict with the expectations of the central nervous system, not only the sensory organs per se, thus neural mismatch (Reason, 1978).

In all types of nauseogenic environments, one sensory system is receiving information that is in opposition to information received by one or more other sensory systems. For example in an environment that produces vection - perceived self motion as in Lishman and Lee's (1973) moving room, the vestibular and somatosensory systems are signalling that the individual is not moving, however, the visual system is signalling that there is definite movement that corresponds to the individual moving. These different cues from the sensory systems are said to be responsible for making the individual sick.

Stoffregen and Riccio (1991) argue that the concept of sensory-conflict theory posits an expectation of redundancy among sensory systems that is not plausible when interacting in the environment. There is non-redundancy in many situations that do not cause motion sickness. Whenever an animal is accelerating, parts of the body will move relative to one another. Movement of the head relative to the optic array will differ from movement of the feet relative to the ground in walking, or from movement of the torso relative to the seat while driving. Stoffregen and Riccio (1991) also argue that motion sickness only occurs in dynamic environments.

In Riccio and Stoffregen (1991) the same authors present a new theory of motion sickness known as the ecological theory, which assumes a link between perception and action. It is further assumed that postural control is fundamental to all behavior and thus to any perception-action interaction between the animal and the environment. The stated premises (p. 205) are that:

> We believe that prolonged postural instability is the cause of motion-sickness symptoms. That is to

> say, we believe that postural instability precedes the symptoms of motion sickness, and that it is necessary to produce symptoms.

Riccio and Stoffregen go on to describe several possible general characteristics or signatures of instability that might be observable in body motions. These include: (1) an increase in gross body motion (wobble); (2) a pattern of increasing acceleration of the center of mass, characteristic of falling; (3) reduced coherence between the motions of different parts of the body, or between the body and the support surface; and (4) higher order moments of the amplitude distribution of postural motion, such as skewness (asymmetries in sway) and kurtosis (flatness/peakedness of the distribution, with flat distributions containing relatively more large-amplitude motions). The present study will in fact examine an index of gross head motion as well as the skewness and kurtosis of the body motion distribution, in accord with Riccio and Stoffregen's signatures (1) and (4). The present study did not measure motion of the body's center of mass, nor of any body part other than the head, and thus cannot address all of their proposed signatures of instability.

Even more recently, a theoretical paper by Ebenholtz, Cohen, and Linder (1994) proposed that eye muscle afference implicates the ocular-cardiac reflex (discussed below) in motion sickness with reflexive nystagmus (and possibly voluntary torsional eye movements) as the cause. Nystagmus is a rhythmic involuntary oscillation of the eyes. Ebenholtz et al. (1994), point to vestibulo-ocular reflexes in support of their theory. They note stimulation of the semicircular canals of the vestibular system by thermal (typically caloric irrigation) or inertial means produces a vestibulo-ocular response (VOR). Moving visual patterns may produce an optokinetic response (OKR). Ocular counterrolling is an otolith-mediated reflex to roll-axis head tilt, and compensatory upward and downward eye movements are the otolith-mediated responses to head pitch (also known as the doll reflex). These reflexes normally support the function of gaze stability.

Based on this tight correspondence between vestibular and oculomotor activity, Ebenholtz et al. (1994) hypothesized that eye movements, controlled by central nervous system vestibular nuclei, and not peripheral vestibular stimulation per se, cause motion sickness. Thus, the absence of vestibular nystagmus and other VORs, not peripheral lesions, might explain why labrynthine-defectives do not get motion sick.

The idea that the eyes are involved in the genesis of motion sickness is an old one. Darwin (1794, cited in Tyler & Bard, 1949) expressed the view that visual disturbances were the principle cause of seasickness. Flack (1931, cited in Chinn & Smith, 1955) believed that ocular muscle imbalance was induced by seasickness and if that imbalance was not induced or aggravated, individuals would not suffer from seasickness. Anecdotally, it has been noted that blind people may become seasick, but there has been no reports on the incidence nor are there detailed reports of the cause of blindness along with incidence of seasickness (Chinn & Smith, 1955; Tyler & Bard, 1949).

Motion Sickness Inducing Environments

Car sickness has plagued passengers since their invention and anecdotally, children are particularly susceptible. Adler (1941) reports that a number of people susceptible to car sickness have been said to have muscle imbalances, particularly hyperphorias. (The term phoria refers to the binocular/dichoptic resting postures of the two eyes. The relative horizontal posture is termed eso- or exo-phoria, the relative vertical posture hyperphoria, and the relative torsional posture cyclophoria.) He further reports seeing cases where correction of heterophoria (mixed types) by prisms relieved patients, particularly children, of car sickness.

In the clinical ophthalmology field, patients with low vision (significant but not total visual loss) are often prescribed telescopic spectacles. This substantial image enlargement may be beneficial, but there is a high number of patients that are unsuccessfully rehabilitated with the spectacles (Demer, Goldberg, Porter, & Schmidt, 1991). Unfortunately, wearing the magnifying glasses results in a different speed of retinal image motion proportional to the optical power of the telescope. Involuntary head movements provoke image movement and often motion sickness occurs similar to the experimental conditions of Shuman (1987).

Perceptual adaptation or optical rearrangement is a field of research in itself. The classic case study was the reinverted retinal image technique that Stratton used on himself (1897). Rearrangement literature included a number of prism studies (subjects wear reversing, mirror, rotated, lateral-displacement, etc. prisms for long periods of time). Ivo Kohler (1974, p. 521) describes nausea in one of his prism adaptation studies:

> The paper by Dr. Uhlarik (Uhlarik, 1974) reminded me of one of our early experiments (during the late 1940s) which, however, we were never able to complete. On the forehead of the subject we attached a small electric motor that rotated binocular and parallel prisms in the frame of a pair of goggles which the subject also wore. The speed was about 2 revolutions/sec^{-1} (depending on the charge of the battery!). This apparatus produced a continuous and regular 'optical earthquake'. Unfortunately, we were unable to go further in this study because the subject became quite nauseated.

Flight

Most of the research activity has centered around environments in the areas of air and space, therefore the majority of this discussion will concentrate in these areas. Air sickness is not uncommon as can be attested to by the ubiquitous air sick bags located conveniently in the back seat pocket of most commercial airplanes. Pilots are also be subject to problematic visual and vestibular inputs therefore careful training is required to teach them to rely on instruments instead of intuition.

One example investigated by subjective report was vection in helicopter pilots. Two hundred and sixty-seven U.S. Coast Guard helicopter pilots were questioned on the occurrence of the vection illusion while flying over water under different light conditions and sea states. The vection illusion had been experienced by 248 of these pilots (93%) and occurred more frequently in low light conditions over rough seas. Flight safety concerns have been raised because pilots may respond to the vection illusion with aircraft control movements (Ungs, 1989) and vection may be a precursor to motion sickness (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990).

Flight simulators

Part of pilot training is the use of flight simulators for safety and cost-effectiveness reasons. Unfortunately, flight simulators may induce motion sickness (Kennedy, Hettinger, & Lilienthal, 1987). Negative consequences of the relationship between simulators and motion sickness include: decreased simulator use, compromised training, and ground and flight safety. Aside from sickness and negative operational consequences, there are also several effects of simulator exposure in general: postural instability, delayed flashbacks and after-effects (a sudden onset of symptoms), shifts in dark focus (the physiological resting position of accommodation), eye strain, and performance changes (Kolasinski, 1995). The not infrequent occurrence of this sickness has caused it to be termed "simulator sickness." A review article by Kolasinski (1995) summarizes forty possible factors associated with simulator sickness from the literature. These factors can be grouped into three major categories: those associated with the individual, the task, and the simulator. Of the 40 factors, 24 are related to vision (including those related to vestibular stimulation which in turn is related to vision) and 12 factors that are related to individual differences. This present study relating to the oculomotor system may provide beneficial information to narrow the search for causes to motion sickness in this and related fields.

Virtual environments

Virtual realities are state-of-the-art for flight simulation, but virtual environments have much broader applications. Teleoperators are the humans who control devices from a "distance." This distance may be as extreme as ground-based personnel assembling the Space Station. The distance could be one of scale such as for performing microsurgery. Virtual environments refer to the synthesized realities generated by computerized displays that are typically visual but may be acoustic, tactile, and force-reflective. Video games are common examples of virtual worlds in the entertainment field, but more elaborate virtual realities are becoming more common place especially in the fields of training and medicine (White, Shuman, Krantz, Woods, & Kuntz, 1990).

The most popular approach to a virtual reality experience is to imbed the user in a 3-D visual environment by using a head mounted display (HMD). The display provides pictorial depth cues on a screen representation, as well as, attempting to simulate binocularly overlapped images so their fusion will create an illusion of a three dimensional world. An additional advantage is some type of 6 degree of freedom tracking device to change the visual perspective as the user moves her head (Mon-Williams, Wann, & Rushton, 1993).

Mon-Williams, Wann, and Rushton (1993) examined the short-term effects on binocular stability in a virtual reality. Twenty subjects used a commercially available HMD for 10 min while cycling around a computer-generated 3-D world. The subjects' phorias were examined before and after this exposure and there were clear signs of induced binocular stress (induced 'phoria) for a number of subjects. Additionally, three subjects felt nauseous after use and one reported motion sickness.

Regan and Price (1994) reported motion-sickness symptoms after a twenty minute (5% of subjects withdrew before that time) immersion in a virtual world. Of 146 subjects, 61% reported symptoms. Not enough specifications on the system are given to propose a cause, but this study points out that virtual reality systems may be very provocative environments for motion sickness.

In a study investigating the trade-off of field-of-view and resolution in a stereoscopically-viewed virtual world, Piantanida, Boman, Larimer, Gille, and Reed (1992) stumbled across a condition that induced motion sickness in all the subjects. The condition was nicknamed by the subjects as "field-of-spew." All subjects experienced some degree of simulator sickness during the course of this study. One factor that seemed to precipitate queasiness was the contrast of the aperture surround. When the surround was black, subjects experienced greater discomfort. Only the black aperture condition produced diplopia; binocular eye movements are again implicated in discomfort.

Space

During the first three days of space adaptation approximately 2/3 of astronauts and cosmonauts experience symptoms similar to those of motion sickness. A significant review of this literature is Connors, Harrison, & Akins (1985). Interestingly, "space adaptation syndrome" has increased for astronauts since the Apollo days. The space shuttle provides the astronauts with more room to move and interact in zero gravity. Like the more conventional motion sickness phenomena (such as sea sickness), the severity or even the occurrence of space adaptation sickness is subject to large individual differences that are poorly predictable. The sickness phenomena are only slightly correlated, for example, with the individual's history in aircraft or other vehicles. Mission effectiveness is compromised to varying extents. Based on the well-known adaptation that abates other forms of motion sickness, attempts have been made to carry out earth-based adaptational procedures so as to shorten or mitigate the space adaptation sickness once aloft. To date these procedures have not enjoyed good success.

The vestibular system is a heavy contributor to acceleration-related discomfort such as the micro gravity of space. The otoliths cease to function without gravity while the semicircular canals continue to register angular acceleration. The outcome of this distortion includes postural and movement illusions, vertigo, and dizziness all of which may lead to space motion sickness. The first report of spatial disorientation in spaceflight was in 1961 from the cosmonaut pilot on the Vostok 2. The pilot felt he was flying upside down immediately after exposure to zero gravity and on his fourth orbit experienced vertigo. On the Voskhod 1 flight the scientist-cosmonaut had an inversion illusion in which he felt half crouched and facing downward. The on-board physician also experienced an inversion illusion in which he felt he was hanging upside down. These illusions persisted whether their eyes were open or shut. It has been reported that of 24 cosmonauts who made flights in Soyuz-type spacecraft 21 experienced postural illusions. During the Apollo and Skylab missions several astronauts reported similar postural illusions as well as movement illusions such as tumbling or spinning sensations (Connors et al., 1985).

Also, dating from the Apollo program, posture and gait instabilities following spaceflight have been reported similar to mal de debarquement. These instabilities reported postflight are purported to result from in-flight adaptive changes in central nervous system processing of sensory inputs from the vestibular, proprioceptive, and visual systems. A study of recovery of postural equilibrium following spaceflight were unable to test 2 of 13 subjects because of such severe motion sickness symptoms (Paloski, Reschke, Black, Doxey, & Harm, 1992). An additional 4 subjects had clinically abnormal scores of postural equilibrium on landing day. Although there was an initial improvement in postural stability within the first 10-12 hours after landing, recovery to pre-flight levels was on the order of 2-4 days.

Bles and de Graaf (1993) have recently suggested using long duration centrifugation as a predictor for space sickness and as a trainer for familiarization with the perceptual illusions encountered during initial contact with the space environment. Several European astronauts have described the experience of centrifugation with 3G loading for 1.5 hours in a supine posture to be similar to space adaptation syndrome.

Low-frequency vibration

An environment that is not as closely tied to the previously mentioned environments is one of vibration. Imposed oscillatory motion of the body can be nauseogenic and this effect is greatest within the range of .1 to .3 Hz (Guignard & McCauley, 1982). The highest amplitudes of normal body sway are between 0 and .4 Hz (Howard, 1986). As previously noted by Shuman (1988), imposed optical oscillation mimicking the frequency and magnitude of body sway may cause nausea.

Gravity and the eye

Steinbach (1992) brings attention to the role of gravity in the visual system itself. It is pointed out that upon consideration of the "eye ball", there are many additional structures that should be included. There is the optic nerve, the extraocular muscles, and all the fascial attachments between muscles and globe and orbit. "These retrobulbar structures move in a sea of fat; in fact, the orbital fat is the dominant feature of dissections of the orbit, a surprise to many neophyte surgeons." The specific gravities of the fat, the optic nerve, and the eye muscles are very important factors in the visual system. "If the optic nerve and muscles have a specific gravity greater than that of the fat, then they would 'sink' in the less dense fat. With the center of mass of the eye not in the same place as the center of rotation, changing the position of the head with respect to gravity could mean that comparable eye movements within the orbit would require different innervation patterns." A non gravity environment like space could in fact force those changes. Environments like parabolic flight, or centrifuges would also directly affect the eye and its structures. Additionally, the placement and amount of an individual's fat padding, and their retrobulbar structures may explain some individual differences to motion sickness susceptibility.

Steinbach (1992) further states that, "when the human is subjected to unusual gravitoinertial forces, anomalies of behavior and perception can occur which might arise from having an eye with non-coincident centers of mass and rotation." Steinbach discusses several possibilities such as: possible changes in the vestibulo-ocular reflex due to eye movements being programmed to a "down" that is no longer defined by gravity; and illusions of motion that also may have some basis in the mechanical effects of linear acceleration on the control of eye position. In this case the "elevator illusion" that subjects experience in a centrifuge (Cohen, 1973) may be due to added g-forces that affect the eyeball itself, rather than the otoliths. These examples all point to the relevance of the eye-muscle afference theory (Ebenholtz et al., 1994).

Oculo-Cardiac Reflex

This section describes a possible physiological link between eye movements and motion sickness symptoms. The oculo-cardiac reflex was described simultaneously by Aschner and Dagnini in 1908 (cited in Milot, Jacob, Blanc, & Hardy, 1983). They discovered that pressure on the eyeball results in slowing of the radial pulse. Since these early observations, several authors have reported serious bradycardia resulting from strabismus surgery. Strabismus is a naturally occurring visual disorder of the ocular muscles. Typically, this is corrected surgically at an early age by shortening one of the ocular muscles which is asymmetric with respect to the others.

The importance of the oculo-cardiac reflex was emphasized by Sorenson and Gilmore (1956) when they described a cardiac arrest caused by traction on the medial rectus muscle during routine strabismus surgery on a three-year old girl. The heart rate returned to normal upon release of the tension on the muscle. Each time tension was applied to the muscle, the pulse rate dropped dramatically.

It has been established in the last 20 years that an oculo-cardiac reflex occurs when there is traction on any extraocular muscle. The anatomic pathway of this reflex has been well described in Katz and Bigger (1970, p. 199).

> The afferent pathway consists of fibers that run with the short ciliary nerves to the ciliary ganglion and then with the ophthalmic division of the trigeminal nerve to the Gasserian ganglion. Afferent fibers also run with the long ciliary nerve and the ophthalmic division of the trigeminal nerve to the Gasserian ganglion. From the Gasserian ganglion both groups of afferent fibers terminate in the main sensory nucleus of the trigeminal nerve in the fourth ventricle. The efferent limb runs in the vagus nerve. Thus, the reflex is trigemino-vagal.

Milot et al. (1983) conducted a study to determine whether the frequency with which the reflex is induced by muscle traction differs between the medial rectus muscle and other extraocular muscles, whether the reflex shows laterality, and whether the frequency of the reflex is related to the type of traction. During strabismus surgery on 81 extraocular muscles in 49 children the cardiac response to calibrated traction on each of the muscles operated on was studied through the use of a micro-displacement transducer and the tachometer of a cardiac monitor. There was no significant difference in the frequency of induction of the oculo-cardiac reflex between the medial rectus and the other muscles. However there were too few other muscles that required surgery so all the other extraocular muscles were compared to the medial rectus. There was no significant difference between the two eyes. There was a significant difference in the type of traction used on the eye muscles. Quick traction provoked a reflex in 87% of instances, while progressive traction did so in only 51% of the instances (Milot, et. al, 1983).

More current research was carried out by Houchin, Dunbar, and Lingua (1992) who were interested in finding a method of anesthesia to make this the oculo-cardiac reflex less likely. The incidence of emesis following strabismus surgery in children undergoing general anesthesia has been reported to range between 60% and 85%. An even higher association has been noted with surgery involving the medial rectus muscle (oblique muscles, by themselves, were not studied). In contrast, the incidence of emesis following general anesthesia for other pediatric procedures ranges from 20% to 55%. Previous studies had found that a retrobulbar block could elicit the oculo-cardiac reflex in 44% of patients. Also, intravenous or intramuscular atropine, while decreasing the incidence of oculo-cardiac reflexes from 71.8% to 29.7%, increased the arrhythmias which were seen. These arrhythmias were more severe and long lasting than those seen in the untreated patients (Katz & Bigger, 1970).

To reduce post-operative emesis by blocking neuronal reflexes stimulated by strabismus surgery, Houchin et al. (1992) assessed the efficacy of supplementary local anesthesia in a randomized, prospective, controlled trial involving 55 pediatric patients.

Emesis occurred in 47% of those receiving retrobulbar anesthesia, while the incidence in controls was a significantly higher 70%. Manipulation of the medial rectus muscle resulted in nausea and vomiting in 92% (12/13) of the controls, while only 30% (7/23) of patients reported symptoms when treated with supplementary local anesthesia. The incidence of emesis in the treated group approximates the incidence following general anesthesia without strabismus surgery. Also mentioned in this study was that there is a high incidence of nausea in closed angle glaucoma patients, glaucoma caused by a blow to the head. It is possible that the pressure on the eye muscles could cause this nausea.

There is other evidence linking oculomotor and cardiovascular systems. Tyrrell, Thayer, Friedman, Leibowitz, and Francis (1992) measured tonic accommodation and tonic vergence during a 28 minute period that was designed to elicit a wide range of autonomic activity. Mean heart rate was positively correlated with tonic vergence so that faster heart rates were associated with nearer tonic vergence positions. The authors suggest autonomic mechanisms may underlie the eye-heart link and additionally these mechanisms may account in part for the individual differences in tonic accommodation and tonic vergence.

Torsional Eye Movements & Depth Perception

Eye Movements and Vestibular Reflexes

The eye muscles responsible for torsional movements are the inferior and superior obliques. The inferior comes in nasally, and rests along the inferior surface of the globe forming an approximately 90 deg oblique angle to the inferior rectus. Contraction results in eye movement upward and inward. The superior oblique also enters nasally, but runs out through a slightly anterior structure called the trochlea (pulley) and returns back to the eye and also forms an approximately 90 deg oblique angle with the superior rectus.

Head movements and eye movements coordinate in order to maintain gaze stability. The involuntary reflexes involved in this activity are designated as vestibulo-ocular reflexes. Each of the 6 semicircular canals of the inner ear (vestibular system) innervates two eye muscles each. The left superior oblique canal innervates the inferior oblique muscle of the right eye and the superior rectus of the left eye which involves movement up and to the left. Finally, the left inferior canal innervates the inferior rectus of the right eye and the superior oblique of the left eye involving movement in the down and left directions.

There are also extensive neural connections via the medial longitudinal fasciculus between the vestibular nuclei and the 3rd (oculomotor - extrinsic eye muscles except for superior oblique, and lateral rectus), 4th (trochlear - superior oblique muscles), and 6th (abducens - lateral rectus eye muscles) cranial nerves. These connections are the reason for the highly correlated activity of the vestibular system and oculomotor system (Ebenholtz et al., 1994).

Torsional Eye Movements

Rotation of an eye about the visual axis is known as ocular torsion. Duke-Elder (1932, cited in Kushner, & Kraft, 1983) credited Hunter as the first person to report objective compensatory ocular torsional movements. In 1786, Hunter described a rolling movement of his eye when he tilted his head while observing his eye in a mirror. In 1866, Javal (cited in Kushner, & Kraft, 1983) came to the conclusion that compensatory ocular torsion existed because he observed that when he tilted his head right or left he was unable to see clearly through his astigmatic spectacles. Conjugate torsion of the two eyes is now known as cycloversion. A form of cycloversion known as ocular counterrolling occurs during lateral head tilt, which is believed to be otolith-mediated. Conjugate rotary nystagmus can be induced by viewing a large rotating field or while flying in a rolling aircraft.

Torsional eye movements are very difficult to record. Traditional methods of ocular movement recording such as the corneal reflex method, electrooculography, or the use of

Purkinje images do not record eye torsion. Methods that rely on photographing the iris landmarks or episcleral blood vessels do not provide a continuous record, must be analyzed frame by frame (typically by eye), and are very time consuming to process. The current preferred method for measuring torsion is the scleral search-coil. This coil is mounted on an annular contact lens. When the coil is placed on an eye within an oscillating magnetic field, a voltage proportional to the sine of the torsional position of the eye is generated (Howard, 1993). There are some drawbacks to the search coil method, however. Subjects may only wear the coils for 30 minutes or less in a session, there is coil slippage on the eye which is difficult to eliminate, and the equipment is quite expensive.

Miller and Graybiel (1971) investigated the counterrolling reflex in deaf subjects with complete functional loss of the semicircular canals and otolith organs. Using the photographic technique and a chair that confined and tilted subjects left or right, the researchers found that there was a small but definite basic counterrolling response in these subjects compared to normals. This eye roll was gravity dependent but apparently independent of peripheral vestibular stimulation in these subjects. This may be related to the mechanical properties described by Steinbach (1992), as reviewed in the section above on "Gravity and the eye."

Ocular counterrolling in the median plane (forward-backward inclination) has been called the doll reflex because of the resemblance of the eye movements to counterweighted doll-eyes. Ebenholtz and Shebilske (1975) used a photographic method to measure the counterroll in subjects confined to a tilt chair that prevented neck movements. It was found that the doll reflex was fit well with a sine function of body tilt. Also, the innervation of the extra-ocular muscles did not contribute directly to the sense of visual direction.

Cyclovergence

In order to maintain stereoscopic imagery, humans must maintain horizontal, vertical, and torsional binocular alignments. Disjunctive torsion, or cyclovergence, is evoked by disparities in the images in the two eyes (Howard, 1991; 1993). Fusional cyclovergence was first studied by Nagel (1861, cited in Crone, & Everhard-Halm, 1975). He established that rotation of horizontal fusion contours produced a cyclovergence, while rotation of vertical contours produced a stereo effect but no cyclovergence.

According to Howard's (1993) detailed analysis, cyclovergence reduces the parallel vergence horopter to a single line in the median plane, inclined according to the degree of torsion. The horopter is the locus of all points in space whose images fall on corresponding points on the two retinas. This reduction of the horopter from a surface to a line, is due to the introduction by cyclovergence of vertical disparities at all points away from the vertical meridian. These vertical disparities are maximal in the horizontal meridian, and where there is a vertical disparity there is no point on the horopter. The only region where all disparities are zero is an inclined line in the median plane. Therefore, the horopter surface (when taking only horizontal disparities into account) is reduced to a line by also considering vertical disparities. In the normal eye, there is no net ocular torsion with fixation in the primary position. Cyclovergence normally occurs when the eyes are converged or when the gaze is directed downward. The convergence-induced cyclotorsion tilts the horopter, and if downward gaze is also introduced the horopter tilts even more (Tyler, 1983).

Kohler (1962) noted the special stereoscopic effects using prism goggles. Typically, a vertical rod appears to the viewer to bend either to the left or to the right, depending on which way the bases face. For the goggles whose prism bases both face outward, forcing convergence, the vertical rod appeared to be bent away from the viewer (pitched).

Crone and Everhard-Halm (1975) using the photographic technique confirmed earlier observations by Nagel that there is a greater effect of horizontal contours than vertical for producing cyclovergence, but rotation of vertical contours can cause cyclovergence. It was also established that the greater the complexity of the stimulus, and the larger the size of the stimulus, the larger the cyclovergence response.

Using scleral search-coil methodology, previous findings of torsion being less stable than horizontal and vertical eye positions were confirmed (Van Rijn, Van der Steen, & Collewijn, 1993). Van Rijn et al., (1994) also found that cyclovergence is more stable than cycloversion. These researchers were also able to show that cyclovergence is made more stable with the addition of a structured visual background for the target. Cycloversion stability was not improved with the addition of the background. The main difference in the two systems is that visual control of cyclovergence contains a static component to maintain binocular correspondence. In contrast, cycloversion control is limited to a dynamic response to changes in visual orientation.

Cyclovergence is driven by cyclodisparity (Van Rijn et al., 1994). Optimum correspondence results from negative feedback control that minimizes any cyclodisparity by appropriate cyclovergence. This means the set-point for cyclovergence is zero cyclodisparity (an unambiguous internal reference) from the comparison of the two retinal images. Cycloversion does not have such a visual set-point. In order for a visual set-point to be available for this oculomotor system, it would be necessary to have both an absolute estimate of orientation of contours on the retina, and knowledge about the objective orientation of the same contours in the world. There is too much variety in object orientations and viewer perspectives for accuracy. Additionally, it was shown that spontaneous ocular torsion was largely conjugate, implying that cyclovergence is controlled better than cycloversion. Interestingly, these researchers also found that two of their four normally sighted subjects exhibited cyclophoria.

Howard (1991) measured torsional eye movements with the scleral search-coil technique and with the psychophysical nonius technique. He showed that human cyclovergence eye movements were driven with much higher gain by vertical disparity than by horizontal disparity, thus cyclovergence is driven more by cyclorotations of horizontal lines than of vertical lines. He suggests that horizontal disparities stereoscopically encode slant in depth (pitch) and should therefore be retained by the visual system, whereas vertical disparities arise only from misalignment of images and may therefore be nulled by cyclovergence.

Relationship of Cyclovergence and Inclination

It would be interesting to simulate the retinal disparities that might be observed if it were possible to force the subjects' cyclovergence to adopt a changed resting position. If the vertical meridia are no longer parallel because of cyclovergence of the eyes, then the retinal images will be rotated slightly about the foveas in directions opposite to each other. There will be a gradient of binocular retinal disparities created by stimuli in the fronto-parallel plane. These disparities will give stereoscopic cues of inclination, namely that this plane is pitched away from vertical. If the plane is inclined with the top farther from the observer, the left eye's retinal image is rotated clockwise relative to the right eye's retinal image. An angular deviation D exists between the images in the two eyes since these images fall on noncorresponding meridia. Ogle (1950) derived the relationship between total angular deviation (D) and the angle of inclination of the pitched plane (I):

$$\mathrm{TAN}\ D = (P/V) * \mathrm{TAN}\ I \qquad \text{Equation 1}$$

Where P is the interpupillary distance and V is the viewing distance. Ogle (1950, pp. 103-105) shows in tabular form that relatively large angles of inclination correspond to small deviation angles and the magnitude of the inclination for a given deviation will increase markedly with the observation distance. For example, a 10 deg inclination of the frontal plane corresponds to an angular deviation D between the images in the two eyes of 0.09° at a viewing distance V of six meters, but an angular deviation D of 2.2° at a viewing distance V of 30 cm.

These inclinations (pitch angles) may seem large enough to be observable to subjects. However, Helmholtz (1889) noted that under normal conditions an average observer experiences a not inconsequential amount of angular deviation between the vertical meridia of their two retinas. This would produce retinal disparities consistent with an inclination or pitch of the fronto-parallel plane, yet we do not perceive this. There was recent support (Siderov, Harwerth, Bedell, & White, 1992) substantiating Helmholtz's supposition that there is a small backward pitch of the vertical horopter although there are significant individual differences. As discussed in Tyler (1983), unless cyclovergence perfectly eliminated cyclodisparity, pitch or inclination would constantly change in our viewing environment with changes in viewing distance, etc. This may be why perceived pitch is not a compelling feature of the fronto-parallel plane.

Ocular Torsion and Motion Sickness

When experimentally training voluntary cyclorotary eye movements, vection and motion sickness-like symptoms were reported (Balliet & Nakayama, 1978a; 1978b). Using a visual feedback procedure, Balliet and Nakayama were able to train two subjects to make conjugate voluntary cycloversional eye movements up to 30° in magnitude. These movements could be made without being driven by a moving visual stimulus. Interestingly, during training and performance of these eye movements illusions related to the subject's own body orientation were reported. Subjects often felt that their heads and bodies were 'rolling laterally' and further described the following (pp. 214-215):

> Accompanying these changes in egocentric orientation were intermittent sensations of stomach nausea, headache, and general body fatigue. The most dramatic of these illusions occurred as a distinct 'hallucinatory barrage' at least twice to each subject during initial training. Associated with eyelid tremor the nearly vertical and parallel lines would appear to move independently, becoming almost horizonal and also appearing curved or wiggly. Accompanying these peculiar visual illusions were very powerful sensations of body flotation and/or rapid downward falling in the direction of the voluntary cyclotorsion.

Wolfe and Held (1980) were curious about the possible influence of the binocular visual system on vection. One of the groups of subjects tested was stereoblind with histories of childhood strabismus. Wolfe and Held postulated three possible outcomes for the involvement of the binocular process in the production of vection (1) The process could resemble torsional and optokinetic nystagmus (OKN) by showing binocularity resistant to the early deprivation that rendered the subjects stereoblind. (2) The process could resemble tilt aftereffects by showing an ability to use binocular stimuli in normal subjects, who show interocular transfer, but not in stereoblind subjects (who have no interocular transfer). (3) The process could resemble none of these by showing an inability to use binocular stimuli for vection.

Subjects were seated within a large rotating vertical cylinder. On the surface of the cylinder were randomly placed 1.5 deg and .5 deg black dots on a white background. The cylinder rotated at 26 deg/sec in either direction. In order to maximize vection, an illuminated fixation target was provided in front of the moving field (this also helped to suppress OKN). Subjects were coached in using a magnitude estimation technique to rate the amount of self-motion. Zero was the rating for stationary and 10 was the rating when the self-motion sensation was maximum during rotation of the cylinder. Subjects were admonished to use sensation of self-motion, not direction or velocity of dots on ratings.

The moving stimulus was illuminated with strobe lights. For dichoptic presentation, red and green filters were placed over the strobes and red and green goggles were worn by the subjects (i.e., anaglyph method). The strobes were yoked electronically so that a flash from one strobe to one eye was accompanied by a flash from the other strobe to the other eye. The delay between the two flashes was adjustable. For monocular conditions only one strobe flashed, and for binocular conditions both strobes flashed. The stroboscopic frequency which produced maximal vection was 15 Hz.

In order to determine the influence of binocular vision on vection, stimuli were used that were identical monocularly but different binocularly. Two conditions of stroboscopic illumination were used: in- and out-of-phase. In-phase meant the two strobes flashed simultaneously at the same frequency while out-of-phase meant the two strobes flashed at the same frequency but alternately (180 deg out of phase). In this out-of-phase condition, the combination of the two strobes flashed twice the frequency binocularly of the in-phase condition. Monocular stimulation was the same for in-phase and out-of-phase conditions. Thus the differences between in-phase and out-of-phase conditions were purely binocular. Wolfe and Held (1980) suggest that this paradigm may be thought of as an extended case of apparent motion produced by stimuli presented sequentially to each eye. If the process that generates vection uses binocular information, the addition of binocular apparent motion might be expected to increase the magnitude of vection over the magnitude of vection for the in phase condition at the same monocular frequency.

It was found that most subjects were consistent in their vection rating despite the fact that the subjects found the rating task hard. The out-of-phase conditions were found to produce consistently greater magnitude estimates of vection than the monocular viewing at the same frequency (in-phase conditions). Also found was that there were no significant differences between normal and stereoblind subjects. Therefore, it was concluded that the processes involved in vection are capable of using purely binocular input. Also concluded, was that these processes were not the same as the ones needed for stereopsis. Circular vection, eye torsion, and OKN are all influenced by binocular input in both normal and stereoblind subjects.

Recently, Diamond and Markham (1991) observed unequal torsional movements of the left and right eyes in a subject who was prone to motion sickness during parabolic aircraft flights and also used their technique on astronauts. In a "blind" experimental design, so the experimenters had no prior knowledge of their subjects' actual severity of space adaptation sickness, the nine astronaut subjects' torsional eye movements were measured during a series of parabolic maneuvers in a KC-135 aircraft. Pre-existing data rated the severity of these astronauts' previous space adaptation sickness. Diamond and Markham found that the amount of disconjugate torsion (cyclovergence) while experiencing gravitational forces varying from 0 G to 1.8 G predicted space adaptation sickness severity. In 1 G there were no differences in cyclotropias between subjects. Never before has any single phenomenon so accurately predicted any motion sickness symptomatology.

Independently, Keith White (personal communication) also observed torsional eye movements (cyclophorias) while running subjects (pilots) on the centrifuge at the Naval Aerospace Medical Research Laboratory (NAMRL). Nine subjects were run although two were unable to complete the experimental protocol because of severe motion sickness. The seven subjects were rotated with resultant gravitational vectors in the body's midsagittal or z-axis of 1.5, 2.0, and 2.5 Gz. Despite statistically significant changes in cyclophorias comparing 1 G to the treatment conditions, there were no reliable trends for increasing cyclophorias with increased Gz across subjects. This lack of a trend highlights the role individual differences play in torsional eye movements.

Hypotheses

Ebenholtz, Cohen, and Linder (1994) implicate reflexive eye movements and the afference from extraocular muscles in motion sickness. Their theoretical paper suggests that the physiological mechanism linking eye movements and nausea is the oculo-cardiac reflex, a presumed trigemino-vagal reflex. Surgeons working on the extraocular muscles while performing corrective surgery for strabismus must take care to avoid cardiac arrest. They may reduce the incidence of post-surgical emesis by a retrobulbar block, eliminating the extraocular muscle afference. Anecdotally, emergency medical technicians are aware that trauma to an extraocular muscle might elicit an immediate vomiting response (Houchin, personal communication).

Alternatively, postural instability including body sway has also been associated with motion sickness. Riccio and

Stoffregen (1991) specifically theorize that instability of postural control causes motion sickness and "dynamical diseases" (e.g., simulator sickness). It is clear that the postural control mechanisms in turn rely heavily on visual input. Lishman and Lee (1975), for example, likened humans to "visual puppets" who respond to visually determined body orientation even when proprioceptive and vestibular senses indicate that the body orientation is something else.

To the extent that oculomotor considerations influence the visual input, and to the extent that postural control mechanisms also influence the oculomotor system (e.g., by vestibulo-ocular reflexes), it is difficult to isolate unequivocal support for either the Ebenholtz, et al. or the Riccio and Stoffregen positions. Perhaps, indeed, it is the very oculomotor conditions which most strongly interact with postural control mechanisms that promote motion sickness symptomatology disproportionately: ocular torsion.

Torsional eye movements are effected by the superior and inferior oblique extraocular muscles, almost always under reflex control by the vestibular system rather than through voluntary control. Torsional eye movements have been linked to motion sickness. Diamond and Markham (1991) were able to predict for a subset of astronauts their ranking on space sickness severity by measuring the degree of ocular torsion those astronauts experienced while in parabolic flight. Voluntary cycloversion or cyclovergence may elicit motion sickness symptoms, as has been reported by Balliet and Nakayama (1978).

I propose to investigate body sway in response to binocularly manipulated stimuli, some of which were designed to drive the cyclotorsional eye movement system. Will viewing these stimuli induce motion sickness? If so, it is expected that for those subjects whose questionnaires show post-experimental motion sickness symptoms, one or more of the possible signatures of postural instability may be found, as predicted by Riccio and Stoffregen (1991) and cited above. Operationally when analyzing the gross extent of body sways or "wobble", signature of instability (1), there may be a significant between-subject factor of motion sickness. Signatures of instability (2) and (3) cannot be tested using the present measurements. Skewness and kurtosis in the distributions of sway motions, Riccio and Stoffregen's signature of instability (4), can be adopted as alternative dependent measures and analyzed with respect to the motion sickness factor.

It is expected that static stimuli will be relatively stabilizing, and that an eyes closed condition will be less stable than when the surroundings are visible, based on the empirical literature. Furthermore, the feedback a subject receives by making lateral movements while watching a vertically oriented grating is different from the feedback received if the grating is horizontal. That is, a lateral head motion is parallel to the horizontal stripes but orthogonal to the vertical stripes. A vertical grating should better stabilize the subjects' lateral movements, and a horizontal grating better stabilize their fore-aft movements. Operationally, these effects would result in the within-subject factor of stimulus condition being related significantly to body sways. Unlike the case with motion sickness, however, there is little theoretical basis from the literature to suggest an optimal signature of body sway to use as the dependent measure.

Lastly, while Cohn and Lasley (1990) and Lasley et al. (1991) found increased body sway to a stationary ambiguously fusible repeating pattern, it is predicted here that body sway will change in response to specific manipulations of retinal disparity, including the gradient of binocular retinal disparities correlated with a pitched frontal plane. If increased body sways result from viewing stimulus conditions that simulate the visual consequences of torsional eye movements, such as the present "pitch" conditions, this supports a rationale for investigating further the relationship between torsional eye movements and motion sickness. In keeping with findings of Crone and Everhard-Halm (1975), and Howard (1991), differences may be found in the present study between horizontal gratings (vertical disparities) and vertical gratings (horizontal disparities) because horizontal contours/vertical disparities elicit greater cyclovergence than vertical contours/horizontal disparities. Vertical contours/horizontal disparities are associated with stereoscopic depth perception rather than with the control of eye movements (Howard & Kaneko, 1994), and it is possible that the horizontal pitch conditions may differ from the vertical pitch conditions on that basis.

CHAPTER 2
METHOD

Subjects

Seventeen male and 16 female undergraduate students participated in this study in partial fulfillment of a course requirement. One subject (female) did not reveal her history of deafness and dizziness until after testing and her data were excluded. This left 15 female subjects. Subjects ranged in age from 18 to 37 years. Most subjects were under 25 years of age.

Subjects with balance or inner ear problems were prevented from participation and subjects were discouraged from using any kind of drug, including alcohol, 24 hours prior to participation. The only other restrictive requirement of the subjects was that their height be between 4' 11'' and 6' 4'' tall due to equipment limitations. Subjects were given credit for one hour of testing.

Materials

Subjects were asked to fill out a Motion History Questionnaire package that included questions about their past experiences, if any, with motion sickness. The package also contained the Motion Sickness Symptomatology Checklist which was a pre- and post- experiment checklist to monitor which, if any, symptoms the subjects were experiencing that may be due to the experiment. These forms have been included in Appendix A. These questionnaires were provided with permission to use by Essex Corporation, Orlando, Florida. The forms have undergone repeated studies to test for their validity and re-test reliability and are frequently used by the NAVY in conjunction with pilot training on simulators (Kennedy, Dunlap, & Fowlkes, 1989; Kennedy, Fowlkes, Berbaum, & Lilienthal, 1992; Kennedy, Lane, Berbaum, & Lilienthal, 1993).

Apparatus

Stimulus Description

The anaglyph method was used to separate stimuli to the left and right eyes in order to control binocular/dichoptic relationships. Red chromatic outputs to the video screen were selected by a matched red filter placed before one of the eyes, and excluded from the other eye by a green filter. Green chromatic outputs were selected for by the green filter but excluded by the red filter. An effort was made to match the spectral outputs from the projector tubes to the red and green filters. The filters that were the best match of those available (a book of filters facilitated the decision) were light red (#D39386) and medium green (#D82401) from Edmund Scientific, Barrington NJ. Two pairs of ski goggles were modified to hold the filters. One pair had the red filter over the right eye and green filter over the left eye and the other pair had the opposite configuration. When viewed through the goggles there was approximately equal brightness for each eye. The luminances of the stimuli as viewed through the filters were measured using a Model 1980 Pritchard Spectra Spot Photometer (Photo Research Corporation, Burbank, CA). The red stimuli viewed through the red filter had a luminance range of 9.30 to 10.10 x 10^{-1} candela/meter^2, the red stimuli viewed through the green filter had a "spill over" luminance of 1.42 x 10^{-1} candela/meter^2. The green stimuli viewed through the green filter had a luminance range of 6.61 to 7.34 x 10^{-1} candela/meter^2, the green stimuli viewed through the red filter had a "spill over" luminance of 0.53 x 10^{-1} candela/meter^2.

Stimulus gratings were either red or green (depending on the condition) for a particular eye but each subject was viewing some combination of red and green stripes for all trials except eyes-closed. Subjects swayed with respect to the display, therefore the stimuli had a range of visual subtenses and spatial frequencies. These ranges were calculated based on the range of subjects' movements from the actual data. The screen was 72 cm high and 99 cm wide. Subjects ranged laterally -8.6 cm to +11.24 cm around the 49.5 cm screen center. Although subjects were positioned at

45 cm from the screen, subjects' viewing distances varied between 26.9 cm and to 57.40 cm from the screen. The range for horizontal subtenses was 35.4 deg to 66.1 deg. In order to calculate the vertical visual subtense, it was necessary to know the range of height above and below the 36 cm center of the screen. The range was 22.8 cm to 42.9 cm. This ±10 cm corresponds to the height of a riser. Risers were used to adjust subject viewing height to be in approximately the center of the screen. The range for horizontal subtenses was 21.6 deg to 57.9 deg.

There were 16 cycles of grating projected onto the surface of the screen for vertical display conditions. The 16 cycles were divided by the range of visual subtenses to calculate the range of frequencies. The horizontal spatial frequencies ranged from 0.24 to 0.45 cycles per degree. There were 11.70 cycles of grating displayed for horizontal conditions. The range for the vertical spatial frequencies was as 0.20 to 0.54 cycles per degree.

There were two broad categories of visual stimuli, static and dynamic. The eyes-closed condition was employed because so much is known about body sway in this condition, such as people tend to sway more with eyes closed than under most conditions when the surroundings are visible. The eyes closed-condition has been grouped with the static conditions. The other static conditions were (a) binocularly aligned true vertical or true horizontal gratings, and (b) dichoptic gratings slanted +/- 2° from vertical (or horizontal) to provide a constant binocularly pitched environment. The latter condition simulated the retinal disparities that might be observed if it were possible to force the subjects' cyclovergence to adopt a changed resting position (see Equation 1).

There were a total of eight dynamic conditions which had pattern changes during the measurement interval. Thirty stimulus positions were presented in each dynamic cycle, four video frames (each lasting 1/30 sec) shown at each position. This required 4.0 seconds to complete each cycle (a dynamic rate of 0.25 Hz). This rate was chosen from three considerations: (1) the video control computer had limited memory, (2) a smooth motion appearance needed to be achieved to drive eye movements effectively, and (3) ocular torsion and body sway responses are both predominant at low frequencies. The appearance of smooth rotations could be achieved with 1/4 deg changes in position about 8 times per sec, which exhausted the available memory with 30 positions. This also limited the range of rotation to +/- 2 deg. Thirteen dynamic cycles were presented during the 52 second measurement interval. A measurement interval of 52 sec was selected to allow for lags in visual driving of the subject's eye movements and body sways, and to optimize use of the subject's participation time.

There were two control and six experimental dynamic conditions. These utilized either predominantly horizontal (four conditions) or predominantly vertical (four conditions) grating orientations. There were three types of dynamic binocular stimulation: roll, pitch, and a combination of both.

Roll describes angular orientation in the frontal plane, and is the kind of retinal image change that corresponds to cycloversion eye movements. This type of stimulation was achieved by presenting each eye with an animation of 30 grating stimuli which deviated from vertical (or horizontal) over a range of -2° to +2° in 1/4° increments. The 30 stimulus sequence in the animation cycle was: -2.0, -1.75, -1.5, ...,+1.5, +1.75, +2.0, +1.75, +1.5,..., -1.5, -1.75. For roll stimulation the right and left eyes' dynamic cycles were presented temporally in-phase. Thus, when the left eye saw the sequence +1.5, +1.75, +2.0, +1.75, +1.5, then the right eye also saw +1.5, +1.75, +2.0, +1.75, +1.5. This minimized binocular retinal disparity at a constant low value and maximized roll with a 4° range.

Pitch describes angular orientation in the sagittal plane, and such retinal image changes correspond with cyclovergence eye movements. Pitch stimulation was achieved by presenting each eye with an animation of 30 grating stimuli which varied over the same range of -2° to +2° in

1/4° increments, but the right and left eyes' dynamic cycles were presented temporally 180 degrees out-of-phase. Thus, when the left eye saw the sequence +1.5, +1.75, +2.0, +1.75, +1.5, then the right eye instead saw -1.5, -1.75, -2.0, -1.75, -1.5. This maximized binocular retinal disparity (4° at the peak) and it maximized change in retinal disparity over time. Average roll angle and perceived roll were both minimized.

A combination of roll and pitch was achieved when the right and left eyes' dynamic cycles were presented temporally 90 degrees out-of-phase. Thus, when the left eye saw the sequence +1.5, +1.75, +2.0, +1.75, +1.5, then the right eye instead saw -0.5, -0.25, 0, +0.25, +0.5; also, when the left eye saw the sequence -1.5, -1.75, -2.0, -1.75, -1.5, then the right eye instead saw +0.5, +0.25, 0, -0.25, -0.5. Consider the first three values for each sequence, these show a constant 2.0° difference between the two eyes. During such portions of the animations the binocular retinal disparity (pitch) was constant and the subject perceived a changing average roll angle. Notice that the fourth and fifth values in each sequence depict decreasing differences between the eyes (1.5° and 1.0° respectively).

During these portions of the animations the binocular retinal disparity (pitch) was perceived as changing and the average roll angle appeared constant. In the conditions temporally 90 degrees out-of-phase the largest binocular retinal disparity corresponded to 2° difference between the eyes. During the first quarter of a cycle, disparity was constant and pitched forward, but average roll changed from -1 to +1. In the next quarter-cycle there was change in retinal disparity over time, the grating pitch moved backward, but roll was constant at +1. In the third quarter cycle, disparity was constant pitched back but average roll changed from +1 to -1. Finally, in the fourth quarter-cycle the grating pitch moved forward, but roll was constant at -1.

The final two dynamic conditions, one each for horizontal and vertical orientation, were termed "jaggies controls." These conditions were designed to control for the aliasing effect of gratings slanting across a pixelated screen, a jagged appearance like stair steps. Screen resolution was not good enough for perfectly straight edges with each slant. Rather, for example, each slanted quasi-vertical stimulus resembled a leaning stack of short segments of vertical gratings. The jaggies controls created stacks of grating segments at the same density as each slant condition, but in the control cases these stacks did not lean. Rather, each step went only one pixel left or right of vertical (or one pixel above or below horizontal) yielding vertical (or horizontal) jaggies. Table 1 provides a summary of stimulus conditions for the first or second

Table 1

Summary of Stimulus Conditions

	Slant of Stimulus Gratings			
Static Conditions	First Half		Second Half	
	L-eye	R-eye	L-eye	R-eye
Eyes Closed	none	none	none	none
True Vertical	0 deg	0 deg	0 deg	0 deg
True Horizontal	90 deg	90 deg	90 deg	90 deg
Vertical Pitch	+2 deg	-2 deg	-2 deg	+2 deg
Horizontal Pitch	92 deg	88 deg	88 deg	92 deg
	Temporal Phase of Stimulus Waveform			
Dynamic Conditions*	First Half		Second Half	
	L-eye	R-eye	L-eye	R-eye
Vertical Roll	0 deg	0 deg	0 deg	0 deg
Vertical Pitch	0 deg	180 deg	180 deg	0 deg
Vert. Pitch & Roll	0 deg	90 deg	90 deg	0 deg
Horizontal Roll	0 deg	0 deg	0 deg	0 deg
Horizontal Pitch	0 deg	180 deg	180 deg	0 deg
Horiz. Pitch & Roll	0 deg	90 deg	90 deg	0 deg
	Displacements from Average Slant			
Jaggies Conditions	First Half		Second Half	
	L-eye	R-eye	L-eye	R-eye
Vertical Jaggies (Average Slant = 0)	-1 pixel changes to** +1 pixel	+1 pixel -1 pixel	+1 pixel changes to -1 pixel	-1 pixel +1 pixel
Horizontal Jaggies (Average Slant = 90)	-1 pixel changes to +1 pixel	+1 pixel -1 pixel	+1 pixel changes to -1 pixel	-1 pixel +1 pixel

Note. *Triangular waveform with 4 sec period, amplitude +/-2 deg of slant. **Each change defines a step. Stimulus dynamics consist of a triangular waveform with 4 sec period, from 15 steps to 0 steps and back to 15 steps.

half of the experiment. This table also indicates what stimulus each eye views.

Stimulus Generation

Animations that were run on a computer provided the stimuli. Several steps had to be completed to create the animations. First, a QuickBASIC (Microsoft, Redmond, WA) program was written for each condition that in the case of the dynamic stimuli went through the full cycle of motion frame by frame. These programs are included in Appendix B. A program called HiJaak PRO (Inset Systems, Brookfield, CT) was used to capture each frame and convert it to a Microsoft Windows-compatible graphical bitmap format (*.BMP file format). Then a program designed to be used in the Windows 3.1 environment, Take ONE (Pearl America, Inc., Seattle), imported, compressed and sequenced the bitmap files into animations. Every condition was structured as a 30-frame animation.

Because there were variable delays with loading and decompressing these animations (some files up to one minute), it was necessary to provide supplemental visible stimuli to maintain the subject's accommodation and vergence at the correct distance. Eight hours of DAZZLE (Worldwide MicroTronics, Inc., Spring, TX) was recorded to videotape and at the same time auditory white noise was recorded onto the tape's sound tracks. This videotape played continuously during subject testing so that the auditory white noise was always presented via the headset worn by the subject. A switch was used to select whether videotape or computer output drove the visual display in front of the subject. While the experimenter was loading and setting up the conditions, the switch was placed so that the videotape was displayed. Each animation was presented beginning approximately 8 sec prior to data collection in order to give the subjects a chance to settle from any transients associated with switching between videotape and computer graphics.

Projector System

To project the computer graphics into an environment for a wide field of view, text, graphics or animations were converted to an RS170A (NTSC composite video) output signal by a Model CHANNEL 1 VGA and NTSC display accelerator board manufactured by Industrial Computer Source, San Diego. The board plugged into a 486-DX4 100 Mhz IBM PC compatible computer. VGA mode 12, 640 x 480 pixel resolution, was utilized for display.

The NTSC output signal was used to drive a SONY NTSC video projector, model VPU-720. This three tube video projector was configured as a front-projection device, controlled by the Sony VPU-720A Power Amplifier and VPU-720K Remote Control Logic. A frame was built to hold the projector at the proper height. The frame was tested to ensure that the projector would not move during the course of the experiment. The projector was suspended by 1/4" steel cable in order to allow for leveling the projector. It was important to be able to level the projector in order to prevent any vertical skew in the perceived pitch of the stimuli. This frame was also designed to permit access to the video projector control panels. One panel was opened to fine tune drive currents for the red and green guns, i.e., relative brightness. Another panel concerned alignments for grid registration, specifically the red tube's (1) horizontal and vertical centering, (2) horizontal and vertical magnification, (3) horizontal and vertical linearity, (4) horizontal and vertical skew, and (5) keystoning. Total brightness and relative brightnesses of red and green were also adjustable on the VPU-720K Remote Control Logic box.

This device rear projected the image on a 3 mil thick, 76.2 x 101.6 cm translucent piece of double-matte Mylar drafting film (DPD-3) that was suspended approximately 45 cm away from and in front of the subject. Because of the rear projection all presented stimuli were left-right reversed. The Mylar sheet was sufficiently diffusing to present an acceptable rear projection image when viewed from the front, without hot spots. This mylar sheet was mounted on a square wood frame attached to a side wall of the room and to the front surface of the data collection device support. This permitted the screen to be as close as possible to the subject. The subject stood below the data collection device. As the subject's postural alignment changed, the head position was recorded from the data collection device to a 386DX 33 MHz IBM compatible computer (to be discussed below).

Position Sensing System

The Position Sensing System (PSS) was the measurement device for locating head position. Change in head position over time was used as a measure of postural sway. The PSS worked on the principle that distance can be determined by measuring the propagation time of a transmitted sound front from a point sound source to a point sound receiver.

Four sound sensing devices were suspended in a plane above the subject's head. The microphones were located at the vertices of a square 100.0 cm apart. This square was mounted horizontally 243 cm above the floor. This square was constructed from aluminum L stock and flat aluminum diagonal cross pieces that were screwed into pegboard and then carefully suspended from the ceiling. These devices detected the sharp clicks from a sound source generator worn on the head.

The subject stood below the sensing devices approximately in line with the intersection of the squares' diagonals. The sound source generator was centered on the subject's headgear to point upward toward the middle of the square. The sound source generator was a common miniature earplug speaker modified to broaden its sound dispersion characteristics by cutting off the protruding plastic that would normally fit in the ear. The source employed an 8 ohm voice coil to move a small ferrous diaphragm and the sound was emitted through the 7 mm diameter hole left after modification (Shuman, 1987). The sound was generated by quickly forcing current through the coil of the earphone. This caused the earphone diaphragm to "click." Because sound travels in air at 331.3 meters per second (or 0.0003313 meters per microsecond) at sea level, distance from the sound source to any one sound sensing device could be measured by counting the number of microseconds required for the travel. This principle was implemented using a Keithley MetraByte (Keithley Instruments, Inc., Taunton, MA) data acquisition card and associated software, discussed below. Shuman (1986) discusses the sensing devices and PSS theory and operation in detail.

Static calibration of the PSS found the resolution of location to be on the order of 0.7 mm, based on the standard deviation of repeated measurements of a stationary source. Resolution during dynamic calibration (moving source) was on the order of 1.5 - 2.0 mm. In this case the source was attached to a record player turntable at a radius of 10.0 cm and rotating 45 revolutions per min.

Keithley MetraByte CTM-05

The MetraByte CTM-05 Counter/Timer Module used an Advanced Micro Devices 9513-A chip (Sunnyvale, CA). This chip contained 5 each 16-bit counter registers that can be independently programmed to perform many different functions. Because they were 16-bit counters, the maximum count was 65535. A count of 65535 microseconds corresponds to a distance of approximately 22 meters (which exceeded the parameters of the experimental room), therefore each counter was sufficient for the present application. Four of the registers were configured to count pulses from the 1 MHz precision clock (described below) and one (counter 5) was configured to generate a repetitive square wave.

Counter 5 was programmed to generate a specific square wave. In the control software (included in Appendix D), the square wave is selectable for 10, 18, or 20 cycles a second. In the present experiment 10 Hz was selected to limit the volume of data points. The square wave may be started or stopped under software control. Therefore, when started, the output state of counter 5 went from "on" to "off" every 20th of a second (1 cycle = 50 msec "on" and 50 msec "off"). The square wave output was used for three purposes. First, it triggered the circuitry that generated a single "click" on the sound source. Second, it was fed back into one of the input bits on the parallel input port. This bit was monitored to inform the software that was controlling the

9513-A chip of the state of the square wave for synchronizing the data collection process. Third, the square wave served to turn on the gates for counters 1 through 4 simultaneously with triggering the click.

Four counters were needed to achieve the acoustic timing task, one for each of the four sensing devices. Therefore, counters 1, 2, 3, and 4 were set to count upward from zero whenever they were gated on. Each gate was controlled by a set-reset flipflop which was turned "on" by the click-triggering square wave, and it latched in the "on" state until reset. Each reset, which turned the counter's gate "off", was derived from the associated sound sensor device, as follows. When the pressure wave from the click hit the diaphragm of the sensing device, the diaphragm produced an impulse into the amplifying circuitry and analog Schmitt trigger of the sensing device. The 24 V swing of this analog circuitry was converted to TTL (i.e., binary 1 or binary 0), which is a +5 V signal (this was observed on an oscilloscope to last approximately 20 to 30 μsec) indicating that the pressure wave had arrived at the sensor. This TTL signal reset or turned "off" the gate for the timer, and it also served as input to a particular bit on the parallel input port. Depending on which bit or any combination of bits was received in the parallel input port, it could be determined which timer(s) to disable. When all four timers had been disabled, or if the square wave was sensed to be "off", then the software saved the counters' contents in BASIC variables, cleared and enabled the counters, and waited until the next "on" of the square wave.

This routine was repeated ten times per sec until the operation had been executed the 600 times required for the one minute duration of the experimental trial. During the first eight sec (80 executions of the above routine) the data were displayed but not stored permanently; during the remaining 52 sec, 520 executions resulted in 520 records of data stored. Each record contained fields for record number, counter 1 time, counter 2 time, counter 3 time, counter 4 time, X-axis position, Y-axis position, and Z-axis position. The latter three fields were derived trigonometrically from the four time measures.

Additional Apparatus

The experimental room that was used for the experimental trials had black walls, floor, and ceiling. Black drop cloths were used to cover equipment in this black room so there were no external visual cues other than those projected onto the display screen. The foam cushion that subjects stood upon was 55 x 60 x 11 cm-thick. This cushion provided a more novel, less stable surface than the floor as well as providing a partial control for the subjects' own footwear.

The head gear was constructed of an adjustable hard hat liner (weighing about 3 oz XX grams) with the sound source centered on top in the center. There was a wire for input from the computer to the source to initiate the clicking. This wire attached to the head gear from the ceiling above and was suspended so as not to touch the subject. A pair of light-weight earphones which were also adjustable fitted over the top of the hard hat liner in order to provide auditory white noise. This white noise was continuously present in order to mask clicks generated by the PSS system and to avoid any auditory cues of distance to the screen.

Subjects also donned a pair of ski goggles fitted with the red and green filters for the anaglyph method. Prior to use, the goggles were treated with Fog Free, an anti-fogging agent (Olympic Mountain Products, Kent, WA). The goggles were vented and the Fog Free further prevented fogging if the subjects sweated a lot. One of the specifications for the goggles was the ability to comfortably fit over the subjects' own eyeglasses.

Procedure

Each subject came to the laboratory and signed an informed consent form. The subject then looked at several stickers placed at different heights on a door and chose which sticker position would be the most comfortable height to view for the next 45 min or so. After this choice was made, outer room lights were dimmed and the subject was asked to complete the Motion Sickness Symptomatology

Checklist as a pre-test. This checklist was part of the Motion History Questionnaire.

While the subject completed questionnaire information the experimental room was set up. Riser(s) were placed under the PSS in front of the visual display screen based on the sticker height the subject selected earlier. There were 3 risers that were composed of seven 2" x 4" 's covered with 48" x 48" x 1/4" of plywood and painted with flat black paint. These risers provided placement of the subjects' eyes at the approximate height of the vertical center of the screen. Distance from the floor to the center of the screen was 180 cm. The upper limit on subject height was 6'4'' as the eye level of these subjects would be 180 cm from the floor. Shorter subjects usually stood on one or more risers.

During an approximately 8 min dark adaptation period that followed completion of the questionnaire, the subject was adjusted to be close to the center of the screen and of the PSS. The subject stood on an "X" marked on the foam cushion (placed on top of and centered on the top riser if risers were used) so that they could be aligned in the same position trial after trial. The subject stood approximately 45 cm from the screen surface.

Once the subject was centered with respect to the screen (consequently also centered beneath the PSS), the subject was given the headgear to wear, fitted with the goggles, and the experimental procedure was explained. The instructions included an explanation of what the subject was wearing on the head and why. The subject was then told to stand with their feet roughly two inches apart around the "X" marked with masking tape (there was some unavoidable variation between subjects due to footwear). The subject was also told to clasp their hands in front to prevent using their arms for balance. Then the subject was told to stand as still as possible and to refrain from making arm movements or noises for each one-minute trial duration. The subject was also informed that a break would be taken half way through the experiment and that breaks could be requested at any time. During testing, a research assistant or an experimenter was in the experimental room with the subject the entire time in order to (1) make sure the subject was following instructions; (2) provide safety assistance should it be necessary; and (3) signal the experimenter at the computer controls in the outside room that the subject was ready for the next trial to begin.

Thirteen conditions were run in each of two sessions (26 trials) for the experiment. The conditions, as discussed in the section on Stimulus Description, included the following: Eyes Closed, Vertical Roll, Vertical Roll and Pitch, Vertical Pitch, Vertical Jaggies, Horizontal Roll, Horizontal Roll and Pitch, Horizontal Pitch, Horizontal Jaggies, True Vertical (static), Vertical Static Pitch, True

Horizontal (static), and Horizontal Static Pitch. The conditions were run in blocks. During pilot testing it appeared that running all the vertical conditions as a block and all the horizontal conditions as a block was more destabilizing than intermixing them. Therefore, conditions were run in three blocks (horizontal, vertical, and eyes-closed) with the order of the blocks picked at random for the first session. Condition order within the first session's horizontal and vertical blocks was also randomized. Orders in the second session were an exact counterbalance of the first session.

After the first session of 13 trials there was a scheduled break. This break was necessary as so much standing still in place was fatiguing. During the break, the subject sat down in the outer room, filled out the Motion History Questionnaire form in dim lighting, and continued to be re-dark adapted for another few minutes. Also during the break, floor fans were set up to cool off the experimental room and the subject if necessary. There was inadequate air conditioning ventilation going into the experimental room, especially for subjects having motion sickness symptoms. Because of the noise that fans would have introduced into the acoustically sensitive environment, it was not possible to have the fans running in the experimental room during testing.

The second session was run with the conditions from the first session run in counterbalanced order. The initial condition a given subject received was also the final condition replicated. In previous testing it was observed that there were pronounced individual differences in perception of brightness for visual stimuli viewed through red and green filters. In order to control for this difference, in the second session the subject was given a pair of goggles with the filter configuration reversed from the first session. If a red filter was over the right eye in the first session then the red filter would be over the left eye for the second session. However, during this experiment there was no subjective report of brightness difference between the two eyes, possibly because this experiment used higher luminances than had the previous experiment.

The second session of 13 conditions completed body sway measurement. Then the subject was seated in the outer room to complete a second copy of the Motion Sickness Symptomatology Checklist, the post-test. During debriefing, any questions the subject had were answered and the subject was typically dismissed. Rarely a subject who reported strong motion sickness symptoms was asked to rest for several minutes before leaving. Table 2 contains a summary of the subject procedure indicating the approximate time for events.

Table 2

Procedure for Subject Participation

Events	Approximate Time(min)
Viewing Height Determination, IRB form, & Symptom Checklist Questionnaire	3
Dark Adaptation & Instructions	8
13 trials	21
Rest Break & Motion History Questionnaire (in dim lighting)	3
Dark Adaptation	3
13 trials	21
Symptom Checklist Questionnaire	1
Total Approximate Time	60

Data Analysis

Data were imported into QuattroPro 5.0 spreadsheets (Borland International, Scotts Valley, CA). One spreadsheet file per session per subject was saved with a separate page per condition. Each condition was plotted on an X-Y graph to search for extreme values. These extremes happened when a subject coughed or spoke, or once when the research assistant dropped a flashlight. Fewer than 20 such points were found out of 436,800 possible points. These extreme points were replaced by interpolating between nearby values. Spreadsheet files were exported to MatLab (The MathWorks, Inc., Natick, MA) for power spectral density analyses, and for calculating derived measures V and V' as discussed in the Results chapter. Spreadsheet files were also exported to SYSTATW5 (Systat Inc., Cambridge, MA) for analysis of variance and multivariate statistical procedures.

There were several cases of missing conditions for subjects because of errors of various kinds. The first two subjects were not run on the Vertical Roll and Pitch condition because the stimuli for this condition had accidently been copied over with stimuli for another condition. Subject 9, a subject who had severe motion sickness symptoms, was unable to complete one minute of data collection in 3 conditions (first session Horizontal Pitch; second session, Vertical Pitch and Vertical Static Pitch).

Subject 9 was also unable to participate in the final trial (Vertical Jaggies). Data were lost due to a computer crash for subject 12's first session Horizontal Static Pitch. Subject 24 was missing one first session condition (Vertical Pitch) because the condition accidently got marked off the checklist as run when in fact it had not been. These missing data cells could not be taken into account by the SYSTAT ANOVA procedures, therefore these subjects' data were not analyzed.

CHAPTER 3
RESULTS

Motion Sickness Questionnaires

Motion sickness symptoms were reported on the Essex Corporation Motion Sickness Symptomatology Checklist which is shown in Appendix A. These self-report questionnaires were administered after the test session and were subsequently scored independently by Essex Corporation. Thirteen subjects reported nausea or dizziness, usually with other symptoms as well. Three of those subjects were excluded from the statistical analyses due to missing data cells, such as from discontinued participation. The other 19 subjects reported various other symptoms (excessive sweating, headache, etc.) in various degrees of severity. Two of those had missing data cells and was excluded. In total, 27 subjects had complete data sets suitable for analysis.

A motion sickness score was assigned to each subject based on the number and severity of their reported symptoms. The minimum score would have a value of zero if no symptoms were reported and the maximum score a value of 55 if all 22 symptoms had maximum severity. The present subjects had scores ranging from 2 to 36; on average the scores obtained on the same questionnaire in a vection study using a flight simulator (Hettinger, et. al., 1990) were about four times smaller. Scores in the present study were analyzed as a between-subjects factor with the expectation that subjects who had a high motion sickness score would exhibit large body sways.

Body Sway Measurement

Figure 1 shows an example plot of one subject's head movements while viewing the vertical roll stimuli. Fore-aft sway shown on the ordinate is graphed against lateral sway shown on the abscissa. Line segments connect the (x, y) coordinates of each of the 520 samples of head position made during the measurement interval. Number of seconds since the beginning of the measurement interval is shown for every fortieth sample to give a rough estimation of the subject's head movements over time. It is clear in Figure 1 that the head movements are complex and that the fore-aft and lateral directions of movement may be interdependent. It is not inherently clear what the best single measure of this complex "wobble" behavior might be, which is why Riccio and Stoffregen (1991) proposed several possible signatures of postural instability.

Body Sway Measure, V

To measure gross body sway or "wobble" it was decided to derive a combined measure for both X and Y axes

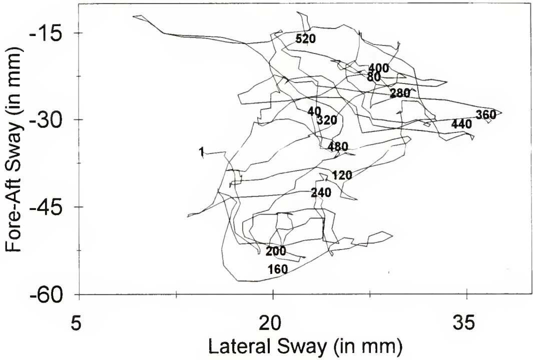

Figure 1. An example of body sway without a mean subtracted. The data displayed are from Subject 1, condition, vertical roll.

(corresponding to lateral and fore-aft directions of body motion, respectively). Each (x, y) position sampled at time t was calculated as deviations from the means of X-axis and Y-axis positions over each trial for each subject (Xavg and Yavg). The deviation from the mean for each axis was squared, the squared deviations were added, and the square root taken of the sum. The measure V is similar to the root mean square error measure used in other laboratories (e.g., Lasley, et al. 1991) except that it collapses sway directions. This combined vector measure showed the effective radius of displacement from center at each time t, the center being at coordinate (Xavg, Yavg), as calculated by the formula:

$$V(t) = ((X(t) - Xavg)^2 + (Y(t) - Yavg)^2)^{1/2} \quad \text{(Equation 2)}$$

A multivariate repeated measures analysis of variance (ANOVA) was carried out for the between-subjects factor of motion sickness score and the within-subject factors of stimulus condition (13 levels) and replication (2 levels). The dependent measure of body sway was mean V (i.e., the sum of the 520 V(t) measured in each trial, divided by 520). The only statistically significant outcome of this analysis was the main effect of stimulus condition, $\underline{F}(12, 180) = 6.85$, $p < .01$. Corrections for repeated measures using Greenhouse-Geisser Epsilon = 0.49 did not change this probability. There was no significant main effect of replication, the other within-subject factor, and no significant interactions of replication with any factor(s). The between-subjects factor motion sickness showed neither significant main effects nor any significant interactions.

The significant effect of stimulus conditions on the measure mean V, the average radius of displacement of the subject's head during a trial, is illustrated by Table 3. This table reports for each condition the group mean of V, in which the average effective radius of displacement for each trial of each subject (mean V) has now been averaged over subjects and replications to yield the group mean V for each condition. These group means range from the minimum 10.19 mm (true vertical condition, hypothesized to be stabilizing) to 14.21 mm (eyes closed, hypothesized to be the least stable condition). Table 3 also reports the standard deviations, across subjects and replications, of the within trial average radii of displacement (mean V) for each condition. These standard deviations range from 3.02 mm (static horizontal pitch condition) to 4.74 mm (horizontal roll condition).

A post-hoc planned comparison using independent samples t-test was carried out for stimulus orientation. Results from the subset of six conditions having horizontal orientations were combined (average = 11.36 mm) and compared to the combined results from the subset of six conditions

Table 3

Group Means and Standard Deviations Across Subjects of the Measure V for the 13 Stimulus Conditions.

Condition Name	Group Mean	S. D.
Vertical Roll	10.60	3.44
Vertical Roll & Pitch	10.21	3.22
Vertical Pitch	10.47	3.34
Vertical Jaggies	10.72	3.44
Horizontal Roll	11.78	3.85
Horizontal Roll & Pitch	10.95	3.75
Horizontal Pitch	11.47	3.64
Horizontal Jaggies	12.18	3.74
Static Vertical Pitch	10.58	4.17
True Vertical	10.19	3.21
Static Horizontal Pitch	10.87	3.02
True Horizontal	10.88	3.39
Eyes Closed	14.21	4.74

having vertical orientations (average = 10.43 mm). This indicated a significant difference, $\underline{t}(646) = 2.79$, $\underline{p} < .05$. Recall that the V measure collapses across the fore-aft and lateral movement axes, and cannot show any interactions between movement direction and stimulus orientation. Lack of independence in the samples will lead to a reduction in the number of degrees of freedom; however, the observed value of the $\underline{t}$ statistic remains statistically significant to 4 degrees of freedom.

In keeping with findings of Crone and Everhard-Halm (1975), De Bruyn, et al., (1992), and Howard (1991), that horizontal and vertical disparities have different oculomotor effects, a second post-hoc planned comparison using independent samples $\underline{t}$-test was carried out for disparity orientation. Results from the subset of four conditions having vertical disparities were combined (average = 11.37 mm) and compared to the combined results from the subset of four conditions having horizontal disparities (average = 10.45 mm). This indicated a significant difference, $\underline{t}(430) = 2.27$, $\underline{p} < .05$. The observed value of the $\underline{t}$ statistic remains statistically significant to 9 degrees of freedom. The planned comparison contrasting the results from eight dynamic conditions as one sample, versus the results from five static conditions as the other sample, was not statistically significant.

The present measures of "wobble", mean V of subject's head motions during body sway, do not support the expectation that the gross extent of body sways correlates with motion sickness symptoms. Riccio and Stoffregen's (1991) possible signature of postural instability (1) is not supported by the present results as a predictor of motion sickness. The V measure is sufficiently sensitive to demonstrate differential effects on body sway of horizontal versus vertical contours, and of vertical versus horizontal retinal disparities. It was not sensitive to dynamic versus static conditions of stimulation nor to fore-aft versus lateral movement distinctions.

Skewness and Kurtosis of Sway Distributions

In accord with Riccio and Stoffregen's (1991) signature of postural instability (4) cited in the Introduction, the skew and kurtosis (third and fourth moments) of body motion distributions were calculated. These distributions were obtained for each trial by each subject in each condition, separately for fore-aft sway (Y-axis), lateral sway (X-axis), and radius of displacement (V). This resulted in 2106 distributions for the 27 subjects who had no missing data cells.

Multivariate repeated measures analyses of variance were carried out separately for the six dependent measures, fore-aft, lateral and radius skew, and fore-aft, lateral and radius kurtosis. Each of these ANOVAs evaluated the effects within-subject factors of stimulus condition (13 levels) and replication (2 levels). There were no statistically significant outcomes of these six analyses. The expectation of Riccio and Stoffregen's (1991) signature (4), that the higher order moments of the body sway distribution might enjoy a non-random association with motion sickness symptoms, appears to have no support from the present analyses. Other derivative measures such as instantaneous speed or instantaneous acceleration of the subjects' movements might result in distributions for which the skew or kurtosis have predictive value, but such analyses have not been reported here.

Fourier Analysis

Fast Fourier transforms (FFT) were calculated for the fore-aft and the lateral sway axes using the first 512 samples (51.2 sec) of each body sway record. See Appendix D for representative sample waveforms and their FFTs. A periodicity in body sway at approximately 0.25 Hz might be observed due to the 4.0 sec dynamic stimulus repetition rate, if the subjects' responses were partially time-locked to the dynamic stimulus motions. The magnitude of the 0.25 Hz component in each body sway FFT was calculated as the absolute value of the complex number result of the FFT.

Multivariate repeated measures analysis of variance was carried out for the dependent measure, magnitude of the 0.25 Hz component in fore-aft sway, the between-subjects factor motion sickness score, and the within-subject factors of stimulus condition and replication. The outcomes of this ANOVA are shown in Table 4. Main effects and interactions were significant in all cases but one; namely, there was no reliable main effect due to replications.

Table 5 shows the means and standard deviations of magnitude of the 0.25 Hz component of fore-aft sway, averaged over the 27 subjects for which the ANOVA is reported in Table 4. These are compiled separately for each replication of each condition.

A post-hoc planned comparison using independent samples $\underline{t}$-test was carried out for static (hypothesized to be stabilizing) versus dynamic conditions of stimulation. Results from the subset of five static conditions were combined (static vertical pitch, true vertical, static horizontal pitch, true horizontal, and eyes closed, average = 313) and compared to the combined results from the subset of the remaining eight dynamic conditions (average = 367). This indicated a significant difference, $\underline{t}(576) = 2.97$, $\underline{p} < .01$. The observed value of $\underline{t}$ remains significant to 14 degrees of freedom for $\underline{p} < .01$ and to 4 degrees of freedom for $\underline{p} < .05$. The planned comparisons contrasting vertical

Table 4.

Multivariate Analysis for Fore-Aft Sway

Source	S. S.	dF	M. S.	F	p	GG
Between Subject Factor						
Motion Sick	4995484	11	454134	5.72	< .01	na
Error	1191276	15	79418			
Within Subject Factors						
Replication	33658	1	33658	1.56	ns	na
R * M	1044952	11	94995	4.42	< .01	na
Error	322400	15	21493			
Condition	2494629	12	207885	5.97	< .01	< .01
C * M	9823205	132	74418	2.13	< .01	< .01
Error	6263828	180	34799			
R * C	915380	12	76281	2.42	< .01	< .05
R * C * M	6469928	132	49014	1.55	< .01	< .05
Error	5676350	180	31535			

Note. GG = Greenhouse-Geiger corrected probability; na = not applicable; R * M = Replication by Motion Sick; C * M = Condition by Motion Sick, Greenhouse-Geiger Epsilon = 0.50; R * C = Replication by Condition, Greenhouse-Geiger Epsilon = 0.53; R * C * M = Replication by Condition by Motion Sick; ns = not significant.

Table 5.

Means and Standard Deviations Across Subjects of the Magnitude of the 0.25 Hz Component for Fore-Aft Sway in the 13 Stimulus Conditions for each Replication.

Condition Name	First Mean (S. D.)	Second Mean (S. D.)
Vertical Roll	358 (201)	259(115)
Vertical Roll & Pitch	335 (141)	312 (157)
Vertical Pitch	365 (215)	333 (187)
Vertical Jaggies	450 (201)	404 (245)
Horizontal Roll	334 (186)	411 (367)
Horizontal Roll & Pitch	362 (190)	351 (188)
Horizontal Pitch	388 (215)	361 (327)
Horizontal Jaggies	402 (277)	442 (306)
Static Vertical Pitch	283 (225)	320 (200)
True Vertical	259 (171)	289 (143)
Static Horizontal Pitch	261 (186)	258 (177)
True Horizontal	319 (207)	239 (125)
Eyes Closed	440 (261)	463 (385)

versus horizontal orientations, and contrasting horizontal versus vertical retinal disparities, were not statistically significant in either case.

Figure 2 plots the magnitude of the 0.25 Hz component as a function of motion sickness score, for each subject. The four panels compare the results from static versus dynamic conditions, obtained in the first or second test (replication). For the two panels labelled as Static Conditions, the five conditions whose results were averaged are listed above, and for the two panels labelled Dynamic Conditions, the results were averaged over the remaining eight conditions.

In the lower left panel, the height of each bar shows for a given subject the mean of the magnitudes found in the static conditions during their first test. The abscissa shows each subject's motion sickness score. The subjects' data are plotted in the same order in each panel.

Notice that the height of the bars in the lower left panel tends to increase from left to right, in the same order as the motion sickness scores increase. This trend is consistent with the main effect of the motion sickness factor on magnitude of the 0.25 Hz component. Similar trends are able to be seen in all four panels of the Figure although there is much variability in robustness. Such variability in the trend is consistent with the interactions between motion sickness and conditions, motion sickness and replications, and with the three-way interaction. The main effect of stimulus conditions can be seen in Figure 2 inasmuch as the two upper panels (dynamic conditions) depict roughly 50% larger magnitudes than do the two lower panels (static conditions).

Just above the top of each bar in the lower left panel the letter M or F is placed to indicate that subject's gender. No reliable effects of gender were found in the previous analyses and the two genders also showed similar distributions of motion sickness scores. However, we note that of the five subjects who had missing data cells, and whose data thus could not be included in the ANOVAs, two were females who reported substantial motion sickness symptoms (scores of 20 and 26) and three were males who reported fewer symptoms (scores of 5, 5, and 9). When these are included to give 32 subjects, then the distributions of motion sickness scores are significantly different for males than for females (Komolgorov-Smirnov two sample test, $\underline{D}(17,15) = 8$, $\underline{p} < .05$). In a future study that might have a larger sample of subjects, the possibility of interactions with gender should be investigated.

Table 6 shows the outcomes when a corresponding multivariate repeated measures analysis of variance was carried out for magnitude of the 0.25 Hz component in lateral sway. The main effect of stimulus condition was

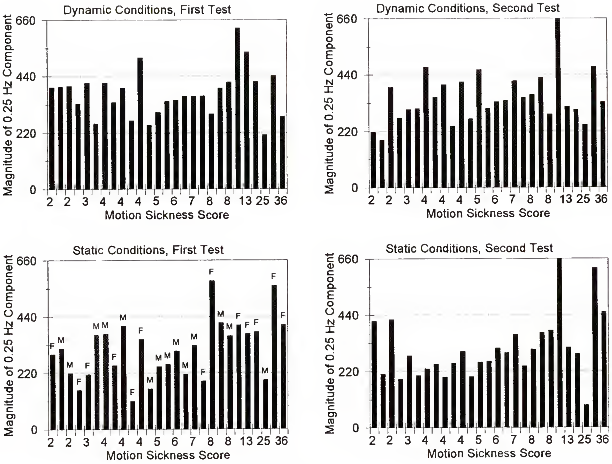

Figure 2. Magnitude of the 0.25 Hz component for the fore-aft sway axis as a function of motion sickness score. Panels compare dynamic and static conditions for first and second tests. Subject order is constant in all four panels. The letters M and F indicate male or female subject.

significant, as was the three-way interaction of replication, condition, and motion sickness factors. Plots for the lateral sway component are roughly similar to those shown in Figure 2 for the fore-aft sway component, but are not shown here.

Table 7 shows the means and standard deviations of magnitude of the 0.25 Hz component of lateral sway, averaged over the 27 subjects for which the ANOVA is reported in Table 6. These are compiled separately for each replication of each condition. Several post-hoc planned comparisons were carried out: for static versus dynamic, vertical versus horizontal orientations, and horizontal disparity versus vertical disparity conditions of stimulation.

Results from the subset of five static conditions, hypothesized to yield stable posture, were combined (average = 200) and compared to the combined results from the subset of the remaining eight dynamic conditions (average = 271), $\underline{t}(694) = 5.41$, $\underline{p} < .01$. This expectation was confirmed, as it had been by the fore-aft axis above.

The planned comparison contrasting the results for vertical orientations (six conditions, average = 218) versus horizontal orientations (six conditions, average = 271), yielded $\underline{t}(608) = 3.64$, $\underline{p} < .01$. This outcome is consistent with the expectation that horizontal gratings are less stabilizing than vertical ones with respect to lateral sways, as hypothesized.

The planned comparison contrasting horizontal retinal disparities (four conditions, average = 214) versus vertical retinal disparities (four conditions, average = 263), yielded $\underline{t}(420) = 2.87$, $\underline{p} < .01$. This is in keeping with findings that horizontal and vertical disparities have different effects on stereoscopic depth perception and oculomotor control. The particular conditions which contrast disparity are a subset of the conditions which contrast orientation, however, and it is not clear from the present results how to assign the partial effects.

The "pitch" conditions, those which presented a gradient of horizontal or vertical retinal disparities consistent with a pitched plane, were surprisingly found to be remarkably stablizing. Both vertical and horizontal dynamic pitch conditions resulted in significantly smaller magnitudes of the 0.25 Hz sway component than did any of the other dynamic conditions, as shown in Table 8. In fact, the dynamic pitch conditions were not reliably different from the static conditions. This finding is quite reliably the inverse of what was hypothesized.

Table 6.

Multivariate Analysis for Lateral Sway

Source	S. S.	dF	M. S.	F	p	GG
Between Subject Factor						
Motion Sick	1968291	11	178935	1.14	ns	na
Error	2361680	15	157445			
Within Subject Factors						
Replication	6154	1	6154	0.22	ns	na
R * M	283531	11	25775	0.93	ns	na
Error	413897	15	27593			
Condition	2690375	12	224198	8.75	< .01	< .01
C * M	4041372	132	30616	1.20	ns	ns
Error	4611200	180	25617			
R * C	103659	12	8638	0.45	ns	ns
R * C * M	4364472	132	33064	1.71	< .01	< .05
Error	3475261	180	19307			

Note. GG = Greenhouse-Geiger corrected probability; na = not applicable; R * M = Replication by Motion Sick; C * M = Condition by Motion Sick, Greenhouse-Geiger Epsilon = 0.41; R * C = Replication by Condition, Greenhouse-Geiger Epsilon = 0.45; R * C * M = Replication by Condition by Motion Sick; ns = not significant.

Table 7.

Means and Standard Deviations Across Subjects of the Magnitude of the 0.25 Hz Component for Lateral Sway in the 13 Stimulus Conditions for each Replication.

Condition Name	First Mean (S. D.)	Second Mean (S. D.)
Vertical Roll	232 (180)	272 (138)
Vertical Roll & Pitch	287 (247)	288 (192)
Vertical Pitch	163 (124)	180 (113)
Vertical Jaggies	223 (129)	202 (127)
Horizontal Roll	371 (308)	403 (255)
Horizontal Roll & Pitch	350 (220)	335 (227)
Horizontal Pitch	211 (104)	227 (133)
Horizontal Jaggies	303 (249)	286 (200)
Static Vertical Pitch	189 (125)	175 (141)
True Vertical	196 (129)	196 (164)
Static Horizontal Pitch	182 (109)	208 (139)
True Horizontal	174 (107)	195 (105)
Eyes Closed	226 (129)	260 (211)

Table 8.

Means, Standard Deviations, Paired t, and Probability for the Planned Comparisons of Pitch Conditions Using the Magnitude of the 0.25 Hz Component in Lateral Sway.

Comparisons	Mean (S. D.)	t(26)	p
Vertical Roll vs	253 (131)	1.02	ns
Vertical Roll & Pitch	288 (173)		
Vertical Roll & Pitch vs	288 (173)	4.39	<.01
Vertical Pitch	172 (88)		
Vertical Roll vs	253 (131)	2.84	<.01
Vertical Pitch	172 (88)		
Horizontal Roll vs	386 (214)	1.25	ns
Horizontal Roll & Pitch	343 (174)		
Horizontal Roll & Pitch vs	343 (174)	3.82	<.01
Horizontal Pitch	219 (92)		
Horizontal Roll vs	386 (214)	4.04	<.01
Horizontal Pitch	219 (92)		
Vertical Roll vs Horizontal Roll		3.22	<.01
Vertical Roll&Pitch vs Horizontal Roll&Pitch		1.69	ns
Vertical Pitch vs Horizontal Pitch		4.04	<.01

Note. ns = not significant.

CHAPTER 4

DISCUSSION

Relationship between Body Sway and Motion Sickness

One purpose of this investigation was to explore a possible relationship between body sway and motion sickness symptoms evoked by the viewing of selected stimuli. Thirteen of the 32 subjects who participated, and ten of the 27 who completed all trials, reported either nausea or dizziness symptoms of motion sickness on a questionnaire administered after viewing these visual stimuli. Motion sickness questionnaires had been administered to 19 subjects who participated in a similar experiment in this same laboratory during the summer of 1993. This previous study was similar in many respects to the current study, but only two out of those 19 subjects reported nausea or dizziness. The method of anaglyph stimulus presentation was also used in 1993 to manipulate retinal disparity but primarily with static stimuli. The hour or more required for testing was similar to the current study, as were ambient conditions such as temperature and humidity. In the current study, for example, eight out of fifteen otherwise asymptomatic subjects reported sweating, while eight out of sixteen otherwise asymptomatic subjects from the 1993 study reported sweating.

The dynamic stimuli used in the present study apparently were unexpectedly efficient in producing motion sickness reports. According to the literature review of Hettinger, et al. (1991), a visual display should evoke a feeling of self-motion (vection) in order to elicit motion sickness symptoms. None of the dynamic stimuli used in the present study moved continuously in the same direction, as do stimuli designed to induce vection, and on this basis would be expected to be weak in inducing motion sickness symptoms. There were no spontaneous reports of self-motion consistent with vection in the present study, although this question was not specifically asked on the questionnaire. Vection was not experienced by the experimenters.

Further investigation into the relationship between binocular retinal disparity and motion sickness seems worthwhile. Reports of motion sickness from viewing a stereoscopic visual display that may have produced diplopia in the users (Piantanida, et al., 1992), and from subjects undergoing diplopia while training cyclovergence eye movements (Balliet & Nakayama, 1978), are in keeping with the present findings that binocularly disparate stimuli may be especially provocative for motion sickness symptoms.

The measurement of body sway and its relationship to motion sickness tested for two of the possible signatures of postural instability proposed by Riccio and Stoffregen (1991), specifically (a) a general "wobble" measurement calculated as root mean squared error (V), and (b) higher-order moments of the sway distributions, skew and kurtosis. Features of subjects' sway that were sensitive to the conditions of visual stimulation seemed to be discriminated by the V measure, although not by skew or kurtosis measures. None of these signatures were sensitive for discriminating subjects' motion sickness scores.

In order to detect relationships between body sway and motion sickness, given the large amount of variability within and between individuals, Fourier analysis was used. The dynamic stimuli moved with a known repetition rate (0.25 Hz) and the body sway responses could be analyzed for components at the corresponding frequency. It was found that the magnitude of this 0.25 Hz component of sway was significantly larger for subjects who had larger motion sickness scores, as illustrated in Figure 2 for the fore-aft sway axis. A similar but weaker trend may be present on the lateral sway axis.

Stimulus Characteristics Influencing Body Sway

A second purpose of the present experiment was to identify characteristics of the visual stimulus conditions which led to increases in body sways. Several specific hypotheses were related to this purpose.

Static visible stimuli are reported in the literature to yield greater postural stability than conditions when the surroundings are not seen (eyes closed). In the present results, the mean V measure (similar to RMS error) did show the eyes closed condition to have yielded the largest "wobbles". The eyes closed condition did not yield the largest magnitude of 0.25 Hz components for either sway axis, although its magnitude was larger than the static conditions' magnitudes on the fore-aft axis.

It was possible to discriminate the effects of vertical orientations from the effects of horizontal orientations with the mean V measure and with magnitude of 0.25 Hz components on the lateral sway axis. Larger sways were found on the lateral axis when viewing horizontal contours rather than vertical contours, as expected. It was not possible to demonstrate differences in sway due to contour orientation for the fore-aft sway axis. Given the differences in visual feedback that may accompany these different orientations the present outcomes are not surprising.

It was also possible to discriminate the effects of horizontal retinal disparities from the effects of vertical retinal disparities with the mean V measure and with magnitude of 0.25 Hz components on the lateral sway axis. Based on the findings of Cohn & Lasley (1990) it is not surprising that horizontal retinal disparity, which supports stereopsis, can influence body sways. Based on the theory advanced by Ebenholtz, et al. (1994) it is not surprising that vertical retinal disparities, which drive torsional eye movements, can also influence body sways. In the present findings, vertical disparities are associated with larger sway measures than are horizontal disparities. However, we are faced with a problem in interpreting this outcome because results on the fore-aft sway axis were so variable. The nature of this problem is that the effects of vertical orientations and horizontal disparities occurred in the same directions in largely overlapping stimulus conditions.

One of the expectations before the experiment was begun was not fulfilled, namely that fore-aft sways would be more effectively stabilized by viewing horizontal gratings rather than vertical gratings. This expectation is because a fore-aft sway has a vertical component that carries the retinal image parallel to a vertical grating but orthogonal to a horizontal grating. Had this expectation been confirmed, the results would have potentially permitted partialling out the effects of orientation separately from the effects of disparity. However, sways along the fore-aft axis were too variable to confirm this expectation. It is speculated that the thick foam cushion that subjects stood upon during testing may have contributed to the more variable sway in the fore-aft direction than in the lateral direction. A future study should adopt a different way of controlling stance.

Lastly, it was hypothesized that body sway would change in response to specific stimulus conditions which included the gradient of binocular retinal disparities correlated with a pitched frontal plane (simulating the effects of torsional eye movements). The present "pitch" conditions do so, using horizontal or vertical disparities in static or dynamic presentations. Based on the correlation between ocular torsion and motion sickness reported by Diamond & Markham (1991), the "pitch" conditions were predicted to be associated with large body sways. The "wobble" measure, mean V, was not sensitive enough to resolve this question because the "pitch" conditions did not differ reliably from the other conditions by this measure.

Magnitude of the 0.25 Hz component for lateral sway revealed significant differences between the two dynamic pitch conditions and all the other dynamic conditions, but the "pitch" conditions gave smaller magnitudes. In fact, the dynamic vertical pitch condition yielded the smallest component magnitude of all the conditions, and the dynamic horizontal pitch condition was not significantly different from the static conditions. This outcome is in the opposite direction to the prediction. However, it is conceivable that the dynamic pitch stimuli failed to time-lock subjects' responses as well as it being conceivable that the responses were small. The pitch conditions might have exhibited more phase noise than the other dynamic conditions because of their heavy reliance on relatively slow binocular fusion and temporal integration (White & Odom, 1985).

Future Directions

The present anaglyph method of binocular stimulus presentation is somewhat crude. The filters used in front of subjects' eyes were not perfect in separating information to each eye. Additionally, the anaglyph method may have promoted binocular rivalry, and individual differences might have been made more prominent by this factor. The possible contributions of binocular rivalry should be minimized more fully in a future study than was possible in the present study. A head-mounted display using two small television monitors with an adjustable interpupillary distance would be closer to ideal.

Further analyses of the present data are worth pursuing in order to more completely resolve some of the results. Additional analyses of Riccio and Stoffregen's signatures of instability using head speed or acceleration may be revealing. Analyzing the phase of the body sway may provide the answer to why dynamic vertical disparity appeared to have the same effect on the 0.25 Hz magnitude component of sway as did static stimuli.

The implications of the study are important to the design of flight simulators and virtual environments.

There are individual differences in the physical structure of the eye and its attachments which may require adaptation by the eye movement system to minimize retinal disparity in an altered gravitational environment. Some individuals may be more sensitive to disorienting effects of retinal disparity. It would be interesting to investigate an additional measure of individual difference of the eye-movement system. Such a measure may be the length of time to perceive a three dimensional object in a random dot stereogram or to what extent of forced convergence or divergence is focus maintained. This type of measure may be correlated with motion sickness and/or body sway.

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APPENDIX A
QUESTIONNAIRES FOR MOTION HISTORY AND SYMPTOM CHECKLIST

Pre-Questionnaire: Physiological Status

1. Have you been ill in the past week? Yes ___ No ___
   If "Yes", specify:
   a) severity,

   b) time course,

   c) where localized, etc.

2. Are you in your usual state of fitness? Yes ___ No ____
3. a) How much alcohol have you consumed during the past 24 hours?

   Number of drinks ________

   b) Are you hung over? Yes ______ No ______

4. Have you taken any drugs or medications of any kind in the past 24 hours?

   Yes ______ No ______

   If yes, were they:

   a) Sedative or tranquilizer ____________

   b) Analgesic (aspirin) ____________

   c) Anti-motion sickness remedy (anti-histamine)_______

   d) Other, (Specify) ____________

5. How many hours sleep did you get last night?__________

   Was this sufficient? _________ Insufficient? _________

6. Circle below if any symptoms apply to you right now. (After the experimental procedure you will be asked this question again.)

1. General discomfort None Slight Moderate Severe
2. Fatigue None Slight Moderate Severe
3. Boredom None Slight Moderate Severe
4. Drowsiness None Slight Moderate Severe
5. Headache None Slight Moderate Severe
6. Eye strain None Slight Moderate Severe
7. Difficulty focusing None Slight Moderate Severe
8. a. Salivation increased None Slight Moderate Severe
   b. Salivation decreased None Slight Moderate Severe
9. Sweating None Slight Moderate Severe
10. Nausea None Slight Moderate Severe
11. Difficulty concentrating None Slight Moderate Severe
12. Mental depression No Yes
13. "Fullness of the Head" No Yes
14. Blurred vision No Yes
15. a. Dizziness with eyes open No Yes
    b. Dizziness with eyes closed No Yes
16. Vertigo No Yes
17. Visual flashbacks No Yes
18. Faintness No Yes
19. Aware of breathing No Yes
20. *Stomach awareness No Yes

* Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Serial #__________________________

Motion History Questionnaire*

1. How often would you say you get airsick?

   Always_______ Frequently_______ Sometimes_______
   Rarely_______ Never_______

2. How much experience have you had at sea aboard ships or boats?

   Much _______ Some _______ Very Little _____ None ______

3. From your experience at sea, how often would you say you get seasick?

   Always ______ Frequently_______ Sometimes_______
   Rarely_______ Never_______

4. Have you ever been motion sick under any conditions other than the ones listed so far?

   No_______ Yes_______
   If so, under what conditions? __________________________
   ____
   ____

5. In general, how susceptible to motion sickness are you?

   Extremely_____Very_____Moderately_____Minimally_____
   Not at all_____

---

*This questionnaire was prepared for research purposes only by R. S. Kennedy and M. E. McCauley. Scoring procedures are available from the authors at: Essex Corporation, 1040 Woodcock Road, Suite 227, Orlando, FL 32803.

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Serial #________________________________

6. Have you been nauseated FOR ANY REASON during the past 8 weeks?

   No _____ Yes _____ If yes, explain ____________________
   ____
   ____

7. When you were nauseated for any reason (including flu, alcohol, etc.), did you vomit?

   Easily _____ Only with difficulty ________
   Retch and finally vomit with great difficulty _________

8. If you vomited while experiencing motion sickness, did you:

   a) Feel better and remain so? ______
   b) Feel better temporarily, then vomit again? _____
   c) Feel no better, but not vomit again? ______
   d) Other - specify ___________________________________
   ____
   ____

9. If you were in an experiment where 50% of the subjects get sick, what do you think your chances of getting sick would be?

   Almost certainly would not _____
   Probably would not _____
   Probably would _____
   Almost certainly would _____

10. Would you volunteer for an experiment where you knew that:
    (Please answer all three)

    a) 50% of the subjects did get motion sick? Yes__ No__

    b) 75% of the subjects did get motion sick? Yes__ No__

    c) 85% of the subjects did get motion sick? Yes__ No__

11. Most people experience slight dizziness (not a result of motion) 3 to 5 times a year. The past year you have been dizzy:

    more than this _____ the same as _____ less than _____
    never dizzy _____

12. Have you ever had an ear illness or injury which was accompanied by dizziness and/or nausea? Yes _____ No _____

Post-Questionnaire

Circle below if any symptoms apply to you right now.

1. General discomfort None Slight Moderate Severe
2. Fatigue None Slight Moderate Severe
3. Boredom None Slight Moderate Severe
4. Drowsiness None Slight Moderate Severe
5. Headache None Slight Moderate Severe
6. Eye strain None Slight Moderate Severe
7. Difficulty focusing None Slight Moderate Severe
8. a. Salivation increased None Slight Moderate Severe
   b. Salivation decreased None Slight Moderate Severe
9. Sweating None Slight Moderate Severe
10. Nausea None Slight Moderate Severe
11. Difficulty concentrating None Slight Moderate Severe
12. Mental depression No Yes
13. "Fullness of the Head" No Yes
14. Blurred vision No Yes
15. a. Dizziness with eyes open No Yes
    b. Dizziness with eyes closed No Yes
16. Vertigo No Yes
17. Visual flashbacks No Yes
18. Faintness No Yes
19. Aware of breathing No Yes
20. *Stomach awareness No Yes

* Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

APPENDIX B
STIMULUS GENERATION PROGRAMS
Written by Keith D. White

QuickBASIC 4.5 Program for Generating Vertical Stimuli

```
'One Screen at a Time
DIM p%(7700, 2): esc$ = CHR$(27)
SCREEN 12: PALETTE 0, 0: PALETTE 2, 63: PALETTE 4, 256 * 63:
PALETTE 6, 257 * 63
RESTORE
'Verticals
FOR s = 1 TO 30: READ i, j
CLS : FOR x = 0 TO 15: LINE (x + i, 0)-(24 + x - i, 479), 2:
NEXT x
GET (0, 0)-(39, 479), p%(0, 0)
CLS : FOR x = 0 TO 15: LINE (x + j, 0)-(24 + x - j, 479), 4:
NEXT x
GET (0, 0)-(39, 479), p%(0, 1)
FOR x = 0 TO 607 STEP 32: PUT (x, 0), p%(0, 0), OR: NEXT x
FOR x = 0 TO 607 STEP 32: PUT (x, 0), p%(0, 1), OR: NEXT x
DO UNTIL a$ = esc$: a$ = INKEY$: LOOP: a$ = ""
NEXT s
END
'red and green in phase... ROLL
'DATA 4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11
'DATA 12,12,13,13,14,14,15,15,16,16,17,17,18,18,19,19
'DATA 20,20,19,19,18,18,17,17,16,16,15,15,14,14,13,13
'DATA 12,12,11,11,10,10,9,9,8,8,7,7,6,6,5,5
'90 deg phase shift... ROLL & PITCH part 1
DATA 4,12,5,13,6,14,7,15,8,16,9,17,10,18
DATA 11,19,12,18,13,17,14,16,15,15,16,14
DATA 17,13,18,12,19,11,18,10,17,9,16,8
DATA 15,7,14,6,13,5,12,4,11,5,10,6
DATA 9,7,8,8,7,9,6,10,5,11
'180 deg phase shift... PITCH
'              D              A              T              A
0,24,1,23,2,22,3,21,4,20,5,19,6,18,7,17,8,16,9,15,10,14,11,1
3
'DATA 12,12,13,11,14,10,15,9,16,8,17,7,18,6,19,5
'DATA 20,4,21,3,22,2,23,1,24,0
```

QuickBASIC 4.5 Program for Generating Horizontal Stimuli

```
'Horizontals
DIM h%(7700, 2)
esc$ = CHR$(27)
SCREEN 12: PALETTE 2, 63: PALETTE 4, 256 * 63: PALETTE 6, 257
* 63
RESTORE
FOR s = 1 TO 30
READ i, j, k, l: 'k,l = 1/2-pixel displacements; 1=down;
0=none ;-1=up
CLS : FOR y = 0 TO 15: LINE (0, y + 22 - i)-(639, y + i + k),
2: NEXT y
GET (0, 0)-(639, 39), h%(0, 1)
CLS : FOR y = 0 TO 15: LINE (0, y + 22 - j)-(639, y + j + l),
4: NEXT y
GET (0, 0)-(639, 39), h%(0, 2)
FOR y = 0 TO 447 STEP 32: PUT (0, y), h%(0, 1), OR: NEXT y
FOR y = 0 TO 447 STEP 32: PUT (0, y), h%(0, 2), OR: NEXT y
DO UNTIL a$ = esc$: a$ = INKEY$: LOOP: a$ = ""
NEXT s
END
'in phase... ROLL
'              D              A              T              A
0,0,1,1,2,2,0,0,3,3,1,1,5,5,0,0,6,6,1,1,8,8,0,0,9,9,1,1,11,1
1,0,0
'              D              A              T              A
12,12,1,1,14,14,0,0,15,15,1,1,17,17,0,0,18,18,1,1,20,20,0,0,
21,21,1,1
'              D              A              T              A
22,22,-1,-1,20,20,0,0,19,19,-1,-1,17,17,0,0,16,16,-1,-1,14,1
4,0,0,13,13,-1,-1
'              D              A              T              A
11,11,0,0,10,10,-1,-1,8,8,0,0,7,7,-1,-1,5,5,0,0,4,4,-1,-1,2,
2,0,0,1,1,-1,-1
'180 deg phase shift...PITCH
'              D              A              T              A
0,22,1,-1,2,20,0,0,3,19,1,-1,5,17,0,0,6,16,1,-1,8,14,0,0,9,1
3,1,-1,11,11,0,0
'              D              A              T              A
12,10,1,-1,14,8,0,0,15,7,1,-1,17,5,0,0,18,4,1,-1,20,2,0,0,21
,1,1,-1
'              D              A              T              A
22,0,-1,1,20,2,0,0,19,3,-1,1,17,5,0,0,16,6,-1,1,14,8,0,0,13,
9,-1,1
'              D              A              T              A
11,11,0,0,10,12,-1,1,8,14,0,0,7,15,-1,1,5,17,0,0,4,18,-1,1,2
,20,0,0,1,21,-1,1
'90 phase shift... some of each
D                   A                   T                   A
0,11,1,0,2,12,0,1,3,14,1,0,5,15,0,1,6,17,1,0,8,18,0,1,9,20,1
,0,11,21,0,1
```

```
DATA
12,22,1,-1,14,20,0,0,15,19,1,-1,17,17,0,0,18,16,1,-1,20,14,0
,0,21,13,1,-1
DATA
22,11,-1,0,20,10,0,-1,19,8,-1,0,17,7,0,-1,16,5,-1,0,14,4,0,-
1,13,2,-1,0
DATA
11,1,0,-1,10,0,-1,1,8,2,0,0,7,3,-1,1,5,5,0,0,4,6,-1,1,2,8,0,
0,1,9,-1,1
```

QuickBASIC 4.5 Program for Generating Vertical Jaggies Stimuli

```
'jaggie artifact for vertical stimuli, LAEXP
DIM p%(7700, 2)
SCREEN 12: PALETTE 2, 63: PALETTE 4, 63 * 256: PALETTE 14, 63 * 257
FOR j = 16 TO 2 STEP -1: m = INT(j / 2) - 1: k = INT(480 / j): l = 2 * k - 1
LINE (0, 0)-(1, k - 1), 2, BF: LINE (0, k)-(1, l), 4, BF
LINE (2, 0)-(15, l), 14, BF
LINE (16, 0)-(17, k - 1), 4, BF: LINE (16, k)-(17, l), 2, BF
GET (0, 0)-(17, k - 1), p%(0, 0)
GET (0, 0)-(17, l), p%(0, 1)
FOR i = 0 TO m: PUT (0, i * l), p%(0, 1), OR: NEXT i
IF j / 2 > INT(j / 2) THEN PUT (0, i * l + 1), p%(0, 0)
GET (0, 0)-(17, 479), p%(0, 2): CLS
FOR x = 0 TO 607 STEP 32: PUT (x, 0), p%(0, 2), OR: NEXT x
DO UNTIL a$ = CHR$(27): a$ = INKEY$: LOOP: a$ = ""
CLS : NEXT j
FOR x = 0 TO 607 STEP 32: LINE (x + 1, 0)-(x + 16, 479), 14, BF: NEXT x
DO UNTIL a$ = CHR$(27): a$ = INKEY$: LOOP: a$ = ""
CLS
FOR j = 2 TO 15: m = INT(j / 2) - 1: k = INT(480 / j): l = 2 * k - 1
LINE (0, 0)-(1, k - 1), 2, BF: LINE (0, k)-(1, l), 4, BF
LINE (2, 0)-(15, l), 14, BF
LINE (16, 0)-(17, k - 1), 4, BF: LINE (16, k)-(17, l), 2, BF
GET (0, 0)-(17, k - 1), p%(0, 0)
GET (0, 0)-(17, l), p%(0, 1)
FOR i = 0 TO m: PUT (0, i * l), p%(0, 1), OR: NEXT i
IF j / 2 > INT(j / 2) THEN PUT (0, i * l + 1), p%(0, 0)
GET (0, 0)-(17, 479), p%(0, 2): CLS
FOR x = 0 TO 607 STEP 32: PUT (x, 0), p%(0, 2), OR: NEXT x
DO UNTIL a$ = CHR$(27): a$ = INKEY$: LOOP: a$ = ""
CLS : NEXT j
```

QuickBASIC 4.5 Program for Generating Horizontal Jaggies Stimuli

```
'jaggie artifact for horizontal stimuli, LAEXP
DIM p%(7700, 2)
SCREEN 12: PALETTE 2, 63: PALETTE 4, 63 * 256: PALETTE 14, 63
* 257
RESTORE
FOR a = 15 TO 2 STEP -1: READ j: m = INT(j / 2) - 1: K =
INT(640 / j): L = 2 * K - 1
LINE (0, 0)-(K - 1, 1), 2, BF: LINE (K, 0)-(L, 1), 4, BF
LINE (0, 2)-(L, 15), 14, BF
LINE (0, 16)-(K - 1, 17), 4, BF: LINE (K, 16)-(L, 17), 2, BF
GET (0, 0)-(K - 1, 17), p%(0, 0)
GET (0, 0)-(L, 17), p%(0, 1)
FOR i = 0 TO m: PUT (i * L, 0), p%(0, 1), OR: NEXT i
IF j / 2 > INT(j / 2) THEN PUT (i * L + 1, 0), p%(0, 0)
GET (0, 0)-(639, 17), p%(0, 2): CLS
FOR y = 0 TO 447 STEP 32: PUT (0, y), p%(0, 2), OR: NEXT y
DO UNTIL a$ = CHR$(27): a$ = INKEY$: LOOP: a$ = ""
CLS : NEXT a
FOR y = 0 TO 447 STEP 32: LINE (0, y + 1)-(319, y + 16), 14,
BF
LINE (320, y)-(639, y + 1), 2, BF: LINE (320, y + 2)-(639, y
+ 15), 14, BF
LINE (320, y + 16)-(639, y + 17), 4, BF: NEXT y
DO UNTIL a$ = CHR$(27): a$ = INKEY$: LOOP: a$ = ""
FOR y = 0 TO 447 STEP 32: LINE (0, y + 1)-(639, y + 16), 14,
BF: NEXT y
DO UNTIL a$ = CHR$(27): a$ = INKEY$: LOOP: a$ = ""
CLS
FOR a = 2 TO 15: READ j: m = INT(j / 2) - 1: K = INT(640 / j):
L = 2 * K - 1
LINE (0, 0)-(K - 1, 1), 2, BF: LINE (K, 0)-(L, 1), 4, BF
LINE (0, 2)-(L, 15), 14, BF
LINE (0, 16)-(K - 1, 17), 4, BF: LINE (K, 16)-(L, 17), 2, BF
GET (0, 0)-(K - 1, 17), p%(0, 0)
GET (0, 0)-(L, 17), p%(0, 1)
FOR i = 0 TO m: PUT (i * L, 0), p%(0, 1), OR: NEXT i
IF j / 2 > INT(j / 2) THEN PUT (i * L + 1, 0), p%(0, 0)
GET (0, 0)-(639, 17), p%(0, 2): CLS
FOR y = 0 TO 447 STEP 32: PUT (0, y), p%(0, 2), OR: NEXT y
DO UNTIL a$ = CHR$(27): a$ = INKEY$: LOOP: a$ = ""
CLS : NEXT a
END
DATA 22,20,19,17,16,14,13,11
DATA 10,8,7,5,4,2
DATA 2,3,5,6,8,9,11
DATA 12,14,15,17,18,20,21
```

```
'jaggie artifact for horizontal stimuli, LAEXP, screen 15

SCREEN 12
FOR y = 0 TO 447 STEP 32: LINE (0, y + 1)-(319, y + 16), 14,
BF
LINE (320, y)-(639, y + 1), 2, BF: LINE (320, y + 2)-(639, y
+ 15), 14, BF
LINE (320, y + 16)-(639, y + 17), 4, BF: NEXT y
DO UNTIL a$ = CHR$(27): a$ = INKEY$: LOOP: a$ = ""
```

APPENDIX C
DATA COLLECTION PROGRAM

Written by Patrick M. Smith with Collaboration
From W. Keith Cudebec for TurboBASIC

```
DIM counters(600,4)
dim x.avg(600)
dim y.avg(600)
dim z.avg(600)
ctmbase%   = &H0300        ' Base ADDRESS
datareg%   = ctmbase% + 0 ' DATA Input/Output port
cmdreg%    = ctmbase% + 1 ' COMMAND port OUTPUT, STATUS port
INPUT
ctmpin%    = ctmbase% + 2 ' Parallel INPUT  port
ctmpout%   = ctmbase% + 3 ' Parallel OUTPUT port
pin7hi%      = &HFF        ' OUTPUT port pin 7 high
pin7lo%    = &H00          ' OUTPUT port pin 7 low
mreset%    = &HFF          ' decimal 255, all bits high
dataptrenable%  = &HE0
dataptrdisable% = &HE8
gatefouton%     = &HE6
gatefoutoff%    = &HEE
alarm1reg%      = &H07
alarm2reg%      = &H0F
mastermodereg%  = &H17
statusreg%      = &H1F
disarmall%      = &HDF
disarm1%        = &HC1
disarm2%        = &HC2
disarm12%       = &HC3
disarm3%        = &HC4
disarm13%       = &HC5
disarm23%       = &HC6
disarm123%      = &HC7
disarm4%        = &HC8
disarm14%       = &HC9
disarm24%       = &HCA
disarm124%      = &HCB
disarm34%       = &HCC
disarm134%      = &HCD
disarm234%      = &HCE
disarm1234%     = &HCF
disarm5%        = &HD0
armall%         = &H3F
```

```
arm1234%          = &H2F
arm1%             = &H21
arm2%             = &H22
arm3%             = &H24
arm4%             = &H28
arm5%             = &H30
holdreg%          = &H10
loadreg%          = &H08
TIMERMASK%        = &h001E '  0000 0000 0001 1110 = 30d
PIOPORT%          = 0
readcmd%          = 0
lbyte%            = 0
hbyte%            = 0
SYNC%             = 0
TIMERCOUNT%       = 0       '  Set received timer mask to 0
THRESHOLD%        = 0
'------------------------------------------------------------------
ctrl.a$ = chr$(1)
ctrl.b$ = chr$(2)
ctrl.c$ = chr$(3)
ctrl.d$ = chr$(4)
ctrl.e$ = chr$(5)
ctrl.f$ = chr$(6)
ctrl.g$ = chr$(7)
ctrl.h$ = chr$(8)
ctrl.i$ = chr$(9)
ctrl.j$ = chr$(10)
ctrl.k$ = chr$(11)
ctrl.l$ = chr$(12)
ctrl.m$ = chr$(13)
ctrl.n$ = chr$(14)
ctrl.o$ = chr$(15)
ctrl.p$ = chr$(16)
ctrl.q$ = chr$(17)
ctrl.r$ = chr$(18)
ctrl.s$ = chr$(19)
ctrl.t$ = chr$(20)
ctrl.u$ = chr$(21)
ctrl.v$ = chr$(22)
ctrl.w$ = chr$(23)
ctrl.x$ = chr$(24)
ctrl.y$ = chr$(25)
ctrl.z$ = chr$(26)
esc$ = chr$(27)
cr$  = chr$(13)
f1$  = chr$(0)+chr$(59)
f2$  = chr$(0)+chr$(60)
f3$  = chr$(0)+chr$(61)
f4$  = chr$(0)+chr$(62)
f5$  = chr$(0)+chr$(63)
f6$  = chr$(0)+chr$(64)
f7$  = chr$(0)+chr$(65)
```

```
f8$  = chr$(0)+chr$(66)
f9$  = chr$(0)+chr$(67)
f10$ = chr$(0)+chr$(68)
f11$ = chr$(0)+chr$(133)
f12$ = chr$(0)+chr$(134)
shiftf9$  = chr$(0)+chr$(92)
shiftf10$ = chr$(0)+chr$(93)
shiftf11$ = chr$(0)+chr$(135)
shiftf12$ = chr$(0)+chr$(136)
up.arrow$    = chr$(0)+chr$(72)
down.arrow$  = chr$(0)+chr$(80)
left.arrow$  = chr$(0)+chr$(75)
right.arrow$ = chr$(0)+chr$(77)
'-------------------------------------------------------------
win.scale% = 550    '150 '75
max.point% = win.scale% * 2
min.point% = - max.point%
   false% = 0
   true%  = NOT false%

   showline%      = false%   'true%
   displayrate    = 0.0 '54

'speedofsound   = 331.3    'm/sec, standard H'book values
speedofsound      =  340.5  *  1000  'mm/sec  by  calibration
                     'Sunday!.wb1
speedofsound##  =  340.5  *  1000  *  .000001  '  mm/us  by
calibration     ' see spreadsheet Sunday!.wb1
micspacing##   = 1000   ' mm
micspacing2##  = 1000 * sqr(2)

pi4th##        = atn(1)
lx##           = 0
ly##           = 0

'-------------------------------------------------------------
MAIN:
   screen 12
   CLS
   paint (0,0),7
```

```
'------------------------------------------------------------
'   Clear out the data array
'------------------------------------------------------------
   for i% = 1 to 600
     for j% = 1 to 4
       counters(i%,j%) = 0
     next j%
     x.avg(i%)=0:y.avg(i%)=0:z.avg(i%)=0
   next i%
TESTDURATION% = 52  ' in seconds
FREQUENCY%    = 10       ' 10 data samples/second
'FREQUENCY%    = 18      ' 18 data samples/second
'FREQUENCY%    = 20      ' 20 data samples/second
DATACOUNT%    = TESTDURATION% * FREQUENCY%
out cmdreg%, mreset%     ' MASTER RESET the 9513
out cmdreg%, disarm5%    ' disarm counter 5
                         '  (Turn OFF square wave)
delay 0.54
out cmdreg%, mreset%     ' MASTER RESET the 9513
out cmdreg%, dataptrdisable%  ' Disable the chip's auto
                         '   register pointer increment
out cmdreg%,  mastermodereg%  ' Set up MASTER MODE register
out datareg%, &HB0       ' 1011 0000  = Low  byte
out datareg%, &HC1       ' 1000 0001 = High byte
                         ' This gives us an FOUT square
                         ' wave of 1 usec (microsec)
for i% = 1 to 4          '  load  the  1st  4  counter's  mode
                         'registers
out cmdreg%,  i%    ' load datapointer with ctr # mode reg
out datareg%, &H28  ' LOW  Byte = 0010 1000
out datareg%, &H8B  ' HIGH Byte = 1000 1011
next i%             ' let count go on low gate, stop on high

out cmdreg%,  &H05  '  load  datapointer  with  counter  5  mode
                         'reg
out datareg%, &H22  ' load counter 5 mode register to reload
                         'from
out datareg%, &H0B  '  load  reg,  BCD  count  up,  and  toggle
                         'output on terminal count.
                    ' LOW  Byte = 0010 0010
                    ' HIGH Byte = 0000 1011
   for i% = 1 to 4       'Counter data registers zeroed
     out cmdreg%,  loadreg% OR i%  '
     out datareg%, &H00 ' Load Reg #i is loaded
     out datareg%, &H00 ' with 0000 0000 0000 0000
   next i%
   out cmdreg%,  loadreg% OR 5    'Load  register  #5  with
                                  'data
   SELECT CASE FREQUENCY%
   CASE 10
   out datareg%, &H50    ' LOW      '  &HC350  (50000D  usec)
                                    'produces
   out datareg%, &HC3    ' HIGH     ' a 1/10 sec square wave
                                    ' on counter #5 output
   CASE 18
   out datareg%, &H81    ' LOW      '  &H6C81  (27777D  usec)
                                    'produces
   out datareg%, &H6C    ' HIGH     ' a 1/18 sec square wave
                                    ' on counter #5 output
   CASE 20
   out datareg%, &HA8    ' LOW      '  &H61A8  (25000D  usec)
                                    'produces
   out datareg%, &H61    ' HIGH     ' a 1/20 sec square wave
                                    ' on counter #5 output
   END SELECT

'-----------------------------------------------------------
'        Begin User Interaction
'-----------------------------------------------------------
IF SubjNumber$="" THEN INPUT "Subject Number> ", SubjNumber$
IF SubjNumber$="" THEN SYSTEM
INPUT "Stimulus Letter> ", CondLetter$
  IF CondLetter$ = ""  THEN SYSTEM
FILENAME$ = "D:\" + SubjNumber$ + CondLetter$ + ".PRN"
'-----------------------------------------------------------
   gosub show.view
'-----------------------------------------------------------
PRINT TIME$;
STARTIME = TIMER
ENDTIME  = STARTIME + TESTDURATION%
   count% = -1              '  Init the data counter
'-----------------------------------------------------------
'             Start the Clicker
'
___________________________________________________________
out ctmpout%, pin7lo%     '  Set the gate latch flip-flops
out ctmpout%, pin7hi%     '  leave latches ready to Clear
   out cmdreg%, &H50      '  010 10000 init     counter 5
   out cmdreg%, arm5%     '  001 10000 start up counter 5
DELAY 8
                          '    (1/10 sec squarewave)
DATALOOP:
     !   inc   count%          'increment record number
```

```
'-----------------------------------------------------------
'Wait for the timer board square wave to be in the HIGH state.
'-----------------------------------------------------------

WAITSYNCON:
      !   mov   dx,ctmpin%     'use PIO to monitor counter 5
      !   in    al,dx          'squarewave state
      !   not   al             'invert PIO input
      !   and   al,&h01        'results in zero unless
                ' desired state
      !   jz    waitsyncon     'do again until desired state
      !   mov   sync%,1          'store sync
'   LOCATE 5,1
'     PRINT USING "SYNC% = #"; SYNC%;
'-----------------------------------------------------------
      !   mov   timercount%,0 'INIT received timer mask
      !     mov dx,cmdreg%
      !   mov   al,&h6f        '011  01111  (LOAD  and  START
                               '1,2,3,4)
     !   out   dx,al
'-----------------------------------------------------------
'Compare the received timer mask with 0000 0000 0001 1110
'-----------------------------------------------------------
WAIT4TIMERS:
      !    mov    ax,timercount% 'If  count  =  mask,  then  4
                               'stopped timers
      !   cmp   ax,timermask%
      !   jne  GETPIO            'GETPIO if count <> mask
      !   jmp  movetohold        'MOVETOHOLD if count = mask
GETPIO:
      !   mov   dx,ctmpin%     ' CTM parallel port address
      !   in    al,dx          ' Get the parallel port
      !   not   ax             ' Flip the bits
      !   mov   pioport%,ax    ' Save all bits in variable
      !   and   ax,&h0001      ' Test bit #1 (Counter #5
                          ' Squarewave-others treated below)
    !   cmp   ax,sync%         ' See if it is same as sync
    !   jz    INSYNC           '  Same  yields  zero,  jump  to
INSYNC
      !   mov   dx,cmdreg%     ' CTM command register address
      !   mov   al,&hCF        ' DISARM timers 1234 command
      !   out   dx,al          ' Turn 'em off
      !   mov   al,&hAF        '   Move   counters   to   hold
registers
      !   out   dx,al          ' Move 'em
      !   mov   sync%,0        ' Reset SYNC variable to LOW
      !   jmp   syncpast       ' Go read HOLD registers
```

```
INSYNC:
      !   mov   ax,pioport%   ' Get the parallel port data
                              'stored above
      !   and   ax,30         ' Only care about 4 bits
                              '(timermask%=0001 1110)
      !   mov   threshold%,ax ' Save the threshold bits
'LOCATE 3,1
'PRINT USING "THRESHOLD% = ##"; THRESHOLD%;
'* TIMERCOUNT% = TIMERCOUNT% OR THRESHOLD%
'      !   or    timercount%,ax
'-----------------------------------------------------------
'If threshold bit(s) active, jump to code representing the bit
'pattern, and stop counter(s), ELSE go back and wait for
'threshold.
'-----------------------------------------------------------
     !   cmp   ax,0
     !   jnz   CK2   'if at least one threshold bit is active
     !   jmp   wait4timers  'if no threshold bits active

CK2:       'threshold bit xxxx xx1x, stop counter 1(x=don't
care)
    !   test   ax,2
    !   jz   CK4               'if not this bit next bit
    !   jmp   L2

CK4: 'threshold bit xxxx x1xx, stop counter 2
    !   test   ax,4
    !   jz   CK8
    !   jmp   L4

CK8:       'threshold bit xxxx 1xxx, stop counter 3
    !   test   ax,8
    !   jz   CK16
    !   jmp   L8

CK16:'threshold bit xxx1 xxxx, stop counter 4
    !   test  ax,16
    !   jz   WAITIMERS
    !   jmp   L16

WAITIMERS:
    !   jmp   wait4timers
L2:        '  CASE 2 0000 0010 - Stop counter #1
      !   mov   dx,cmdreg%
      !   mov   al,&hC1        'disarm1%
      !   out   dx,al
      !   jmp   wait4timers
L4:        '  CASE 4 0000 0100 - Stop counter #2
      !   mov   dx,cmdreg%
      !   mov   al,&hC2        'disarm2%
      !   out   dx,al
      !   jmp   wait4timers
```

```
L8:        '  CASE 8 0000 1000 - Stop counter #3
      !   mov   dx,cmdreg%
      !   mov   al,&hC4        'disarm3%
      !   out   dx,al
      !   jmp   wait4timers
L16:       '  CASE 16     0001 0000 - Stop counter #4
      !   mov   dx,cmdreg%
      !   mov   al,&hC8        'disarm4%
      !   out   dx,al
      !   jmp   wait4timers
'-----------------------------------------------------------
MOVETOHOLD:        'save counters 1,2,3,4  in hold reg
                   'Mode N: data xfer into Hold register on gate
                   'pin low-to-high transition provided by Set
'out ctmpout%, pin7lo%         'Set the gate latch flip-flops
'out ctmpout%, pin7hi%         'leave latches ready to Clear
     !   mov   dx,cmdreg%
     !   mov   al,&hAF
     !   out   dx,al
'-----------------------------------------------------------
WAITSYNCOFF:
      !   mov   dx,ctmpin%
      !   in    al,dx
      !   xor   al,&hff
      !   and   al,&h01
      !   jnz   waitsyncoff
      !   mov   sync%,0

'-----------------------------------------------------------
'   Save the four counter values in the counter array
'-----------------------------------------------------------
SYNCPAST:
  for i% = 1 to 4
  readcmd% = holdreg% OR i%
  out cmdreg%, readcmd%
  lbyte% = INP(datareg%)
  hbyte% = INP(datareg%)
  word  = (hbyte% * 256) + lbyte%
  counters(count%,i%) = word
next i%
```

```
'-----------------------------------------------------
'   Display the point on the screen
'-----------------------------------------------------
       t1## = counters(count%,1)
       t2## = counters(count%,2)
       t3## = counters(count%,3)
       t4## = counters(count%,4)
c                 a                 l                 l
GETXYZ(t1##,t2##,t3##,t4##,x##,y##,z##,x2##,y2##,x3##,y3##,z
2##,xavg##,yavg##)

x.avg(count%)=xavg##:y.avg(count%)=yavg##:z.avg(count%)=z##
    locate 5,1
   print using "Record ####"; count%
   locate 16,1
   print using "Mic 1 #####"; t1##
   locate 17,1
   print using "Mic 2 #####"; t2##
   locate 18,1
   print using "Mic 3 #####"; t3##
   locate 19,1
   print using "Mic 4 #####"; t4##
    if x## < min.point%  then x## = min.point%
    if x## > max.point%  then x## = max.point%
    if y## < min.point%  then y## = min.point%
    if y## > max.point%  then y## = min.point%
    pset (x##,y##),15
'-----------------------------------------------------
'If we haven't collected all our data points, go back and
'collect some more.
'-----------------------------------------------------
'   if count% < DATACOUNT% then goto DATALOOP
out ctmpout%, pin7lo%    'SET gate latch flip-flops
out ctmpout%, pin7hi%    'leave ready for CLR
   !     mov  ax,count%
   !     cmp  ax,DATACOUNT%
         !    jge  TESTEND
   !     jmp  DATALOOP

'-----------------------------------------------------
TESTEND:
   STOPTIME = TIMER
   out cmdreg%, disarm5%           ' disarm counter 5
                                   '  (Turn OFF square wave)
   locate 7,1
   PRINT "End at > "; TIME$
   PRINT
   PRINT USING "Duration > ###.# sec."; STOPTIME - STARTIME
   PRINT
   PRINT USING "Record Count > ####"; count%
   'delay 2.5
'-----------------------------------------------------
```

```
'   Save the data in the data file.
'---------------------------------------------------------------
save.data:
OPEN FILENAME$ FOR OUTPUT AS #1          'write to RamDrive D:
P     R     I     N     T                        #     1     ,
"Subject#";",";SubjNumber$;",";"Condition";",";CondLetter$;"
,";
PRINT #1, "Date>";",";date$;",";"Time>";",";time$;
PRINT #1,""
PRINT #1, "Record#";",";"Mic1";","; 'filename.PRN ready for
PRINT #1, "Mic2";",";"Mic3";",";"Mic4"; 'import  via  Quattro
                                         'menu
PRINT #1, ",";"x-axis";",";"y-axis";
PRINT #1, ",";"z-axis";
PRINT #1, ""
   for i% = 1 to count%
     PRINT #1, USING "#### "; i%;
     for j% = 1 to 4
       PRINT #1, ", ";
       PRINT #1, USING "###### "; counters(i%,j%);
     next j%
PRINT #1, ",";                       'note...earlier versions
PRINT #1, USING "####.## ";x.avg(i%); ' did not store x,y,z
PRINT #1, ",";                        ' with the raw data
PRINT #1, USING "####.## ";y.avg(i%);
PRINT #1, ",";
PRINT #1, USING "####.## ";z.avg(i%);
PRINT #1, ""
next i%
   CLOSE #1
rem       shell.string$ = "COPY " + FILENAME$'note... earlier
                           'versions used these commands to  .
rem       shell shell.string$      'copy from RamDrive D:
                                'to hard drive C:
```

```
'-----------------------------------------------------------------
'   Display the data for experimenter.
'-----------------------------------------------------------------
'show.data:

'gosub show.view
'Display the data
'for data.point% = 2 to count%
'in.key$ = inkey$
'if in.key$ = esc$  then system
'if in.key$ = " "  then
'pset (x##,y##),15
'in.key$ = ""
'while in.key$ <> " "
'in.key$ = inkey$
'wend
'end if
'if in.key$ = f1$  then  ' Add a delay to each point display
'displayrate = displayrate + 0.054
'end if
'
'if in.key$ = f2$  then  ' Subtract delay until 0
'displayrate = displayrate - 0.054
'if displayrate < 0  then displayrate = 0
'end if
't1## = counters(data.point%,1)
't2## = counters(data.point%,2)
't3## = counters(data.point%,3)
't4## = counters(data.point%,4)
'               c              a              l              l
GETXYZ(t1##,t2##,t3##,t4##,x##,y##,z##,x2##,y2##,x3##,y3##,z
2##,xavg##,yavg##)
locate 5,1
'print using "Record ####"; data.point%
'locate 7,1
'print using "x: #####.##"; x.avg(data.point%);
'locate 8,1
'print using "y: #####.##"; y.avg(data.point%);
'locate 9,1
'print using "z: #####.##"; z.avg(data.point%);
'locate 11,1
'print using "delay #.### sec."; displayrate;
'x##=x.avg(data.point%):y##=y.avg(data.point%)
'lx##=x.avg(data.point%-1):ly##=y.avg(data.point%-1)
'if showline% = true%  then line (lx##,ly##)-(x##,y##),6
'    if x## < min.point%  then x## = min.point%
'    if x## > max.point%  then x## = max.point%
'    if y## < min.point%  then y## = min.point%
'    if y## > max.point%  then y## = min.point%
'    pset (x##,y##),6
'    pset (x##,y##),15
```

```
'lx## = x##
'ly## = y##
'   if displayrate > 0  then
'   delay displayrate
'   end if
'   next data.point%

'   gosub wait.key
'  if in.key$ = f10$  then goto show.data
    GOTO MAIN
    SYSTEM
'------------------------------------------------------------
wait.key:
    in.key$ = ""
    while in.key$ = ""
      in.key$ = inkey$
    wend
    return

'------------------------------------------------------------
show.view:
    screen 12
    cls
    paint (0,0),7
    locate 2,1
      print "File "; filename$;
    locate 1,45
      print "S C R E E N";
    locate 1,26
      print "M4";
    locate 27,26
      print "M1";
    locate 27,74
      print "M2";
    locate 1,74
      print "M3";
    locate 3,1
      print using "View #### mm square"; win.scale%*2
    locate 28,47
      print "Top View"
    view (200,20)-(600,410),,11
    window (-win.scale%,-win.scale%)-(win.scale%,win.scale%)
    cls
```

```
'   Draw the mics and perimeter outline
    circle (-500,-500),11,2
    circle (-500, 500),11,2
    circle ( 500, 500),11,2
    circle ( 500,-500),11,2
    line (-500,500) - (-500,-500), 7,, &haaaa
    line (-500,-500) - (500,-500), 7,, &haaaa
    line (500,-500) - (500,500), 7,, &haaaa
    line (500,500) - (-500,500), 7,, &haaaa
'   Crosshairs at 0,0
    line   (-750,0)-( 750,0),7,, &haaaa
    line   (0,750 )-(0,-750),7,, &haaaa
    return
'------------------------------------------------------------
showstatus:
    status% = inp(cmdreg%)
    print "status register = "; hex$(status%)
    return
'------------------------------------------------------------
    end
'------------------------------------------------------------

SUB
GETXYZ(t1,t2,t3,t4,x##,y##,z##,x2##,y2##,x3##,y3##,z2##,xavg
##,yavg##)
shared speedofsound##,micspacing##,micspacing2##,pi4th##
local d1##,d2##,d3##,d4##,x12##,x43##,y13##,y24##,z1213##
d1## = (t1-137)*speedofsound##  ' mm corrected by intercept
                              'and slope
d2## = (t2-137)*speedofsound##  ' mm calibrated in
                              'spreadsheet
d3## = (t3-137)*speedofsound##  ' mm Sunday!.wb1; slope =
                              '2936 usec/m
d4## = (t4-137)*speedofsound##  ' mm intercept (analog
                              'delays)=137 usec
x12## =
(((d1##*d1##)-(d2##*d2##)+(micspacing##*micspacing##))/(2*mi
cspacing##))
x43## =
(((d4##*d4##)-(d3##*d3##)+(micspacing##*micspacing##))/(2*mi
cspacing##))
y14## =
(((d1##*d1##)-(d4##*d4##)+(micspacing##*micspacing##))/(2*mi
cspacing##))
y23## =
(((d2##*d2##)-(d3##*d3##)+(micspacing##*micspacing##))/(2*mi
cspacing##))
x13## =
(((d1##*d1##)-(d3##*d3##)+(micspacing2##*micspacing2##))/(2*
micspacing2##))
```

```
y        2        4        #        #                          =
(((d2##*d2##)-(d4##*d4##)+(micspacing2##*micspacing2##))/(2*
micspacing2##))
if (d1##*d1##) < ((x12##*x12##)+(y14##*y14##)) then
       z1213## = 0
   else
      z1213## = SQR ((d1##*d1##)-(x12##*x12##)-(y14##*y14##))
   end if
   x##  = x12##-(micspacing##/2)
   y##  = y14##-(micspacing##/2)
   x2## = x43##-(micspacing##/2)
   y2## = y23##-(micspacing##/2)
   xt## = x13##-(micspacing2##/2)
   yt## = y24##-(micspacing2##/2)
   x3## = xt##*cos(-pi4th##) + yt##*sin(-pi4th##)
   y3## = yt##*cos(-pi4th##) - xt##*sin(-pi4th##)
   xt## = x3## + (micspacing##/2)
   yt## = y3## + (micspacing##/2)
     if ((xt##*xt##)+(yt##*yt##)) <= (d1##*d1##) then z2## =
sqr ((d1##*d1##)-(xt##*xt##)-(yt##*yt##))

   xavg## = (x3##+x2##+x##)/3
   yavg## = (y3##+y2##+y##)/3
   z## = z1213##
END SUB
```

APPENDIX D

FAST FOURIER TRANSFORMS

Fast Fourier transforms (FFT) were calculated separately for the fore-aft and lateral sway axes using the first 512 samples (51.2 sec) of each body sway record. This process is illustrated by Figures 3 through 6, which represent the same data set that was plotted as spatial coordinates in Figure 1 (page 108 above). Figure 3 shows how fore-aft position of the head changed over time when subject 1 viewed vertical roll stimuli. The mean position over the entire 52.0 sec record has been subtracted from each sample before plotting and before submitting the results to FFT analysis. This waveform shows irregular oscillations in which the subject leans back (aft) as much as 20 mm, or leans forward (fore) as much as 20 mm, relative to their mean position in the measuring device. There is considerable variability in the size and periodicity of these oscillations. Some subjects' records showed smaller and other subjects' records showed larger total excursions than the 40 mm excursion shown in Figure 3. Other details of the waveforms differ substantially from subject to subject, as well as from trial to trial for a given subject, but the waveform displayed is not an unusual one as judged by eye. For FFT analysis of this waveform, each of the 512 samples of fore-aft position (minus average position) was submitted as a one-dimensional array of real numbers to the FFT algorithm of Quattro Pro for Windows 5.0 software (Borland Corp.). The results returned are a one-dimensional array with 512 complex number values. Half of these values represent positive frequencies (looking forward in time) and the other half represent negative frequencies (looking backward in time). Positive and negative frequencies show perfectly correlated FFT results for real number input, as in the present case. The complex number values for the positive frequency half of the FFT results array were converted to real number results, magnitude and phase angle. Magnitude corresponds to the absolute value of the complex number, the length of a vector from its origin in the complex plane to the coordinate specified. Phase corresponds to the angle of the said vector in the complex plane, also known as the argument of the complex number. Figure 4 shows FFT magnitude as a function of frequency obtained by analyzing the waveform shown in Figure 3, the fore-aft axis of the subject's movements. Low frequencies have large magnitudes and higher frequencies have smaller magnitudes. The frequency of interest for the present analysis (0.25 Hz) is near the middle of Figure 4. Figure 5 shows lateral position of the subject's head as a function of time, for the record corresponding to Figures 1 and 3. This subject's left-right movements fell within about plus and minus 15 mm of their average position within the measuring device, and show irregular oscillations. Figure 6 shows FFT magnitudes as a function of frequency for the waveform depicted in Figure 5. Analysis of the phase information, which also follows from FFT analyses, appeared initially to be unpromising inasmuch as the 0.25 Hz region of interest seemed too variable. Perhaps post hoc reanalysis of the phase information is now warranted, as discussed above (page 112), because analysis of the FFT magnitudes has suggested that phase noise (high variability) might be a factor in the "pitch" conditions. (K. D. White, personal communication, April 23, 1996)

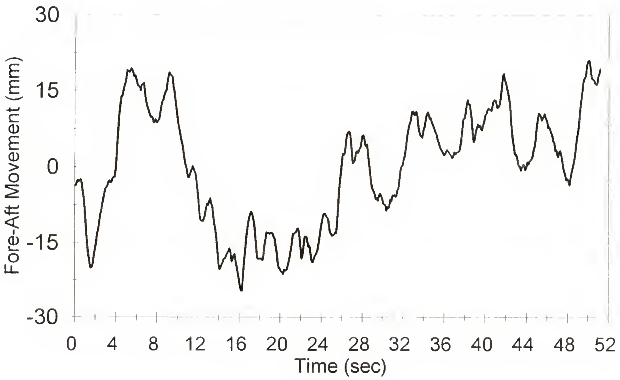

Figure 3. Sway waveform on the fore-aft axis, subject 1, condition vertical roll.

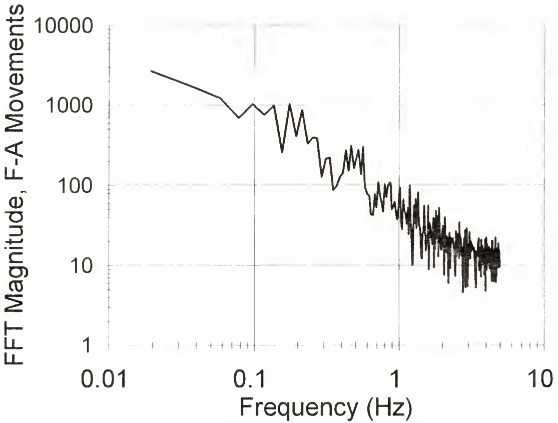

Figure 4. FFT magnitudes for the sway waveform shown in Figure 3.

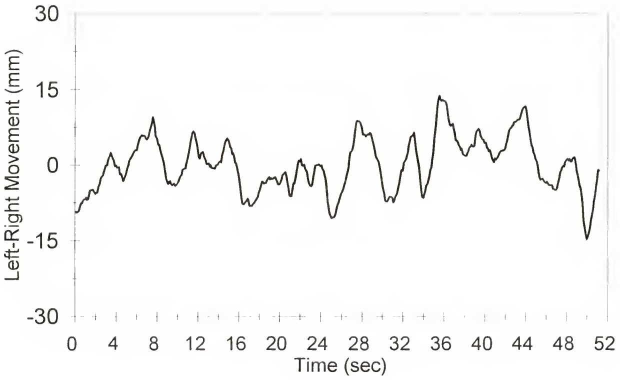

Figure 5. Sway waveform on the lateral axis, subject 1, condition vertical roll.

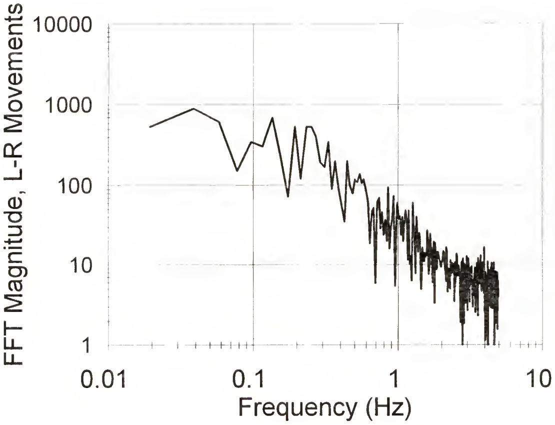

Figure 6. FFT magnitudes for the sway waveforms shown in Figure 5.

BIOGRAPHICAL SKETCH

Lois-Ann Kuntz was born in of all places Gainesville, Florida. However, the family soon settled into Alto, Georgia, where she grew up. Fortunately, some of her mother's creativity rubbed off on Lois-Ann as well as a love of science from her father.

Ms. Kuntz graduated from the University of Georgia in 1984 then was accepted into the master's degree program in industrial/organizational psychology at the University of Central Florida which she graduated from in 1986. During an internship in that program, Lois-Ann discovered the riveting (to her) field of visual-vestibular interaction and its discomforting role in motion sickness. This meant back to school for Lois-Ann. She has recently had her interest piqued in the roles of the visual and the vestibular systems in Parkinson's disease and hopes to pursue research in that area.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Keith D. White

Keith D. White, Chairman
Associate Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

W. Keith Berg

W. Keith Berg
Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

David M. G

David M. Green
Graduate Research Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Scott K. Griffiths
Assistant Professor of Communication
Disorders and Processes

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Robert D. Sorkin
Professor of Psychology

This dissertation was submitted to the Graduate Faculty of the Department of Psychology in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

May 1996

Dean, Graduate School